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MEASURING TECHNOLOGICAL CHANGE IN JET FIGHTER AIRCRAFT.(U)

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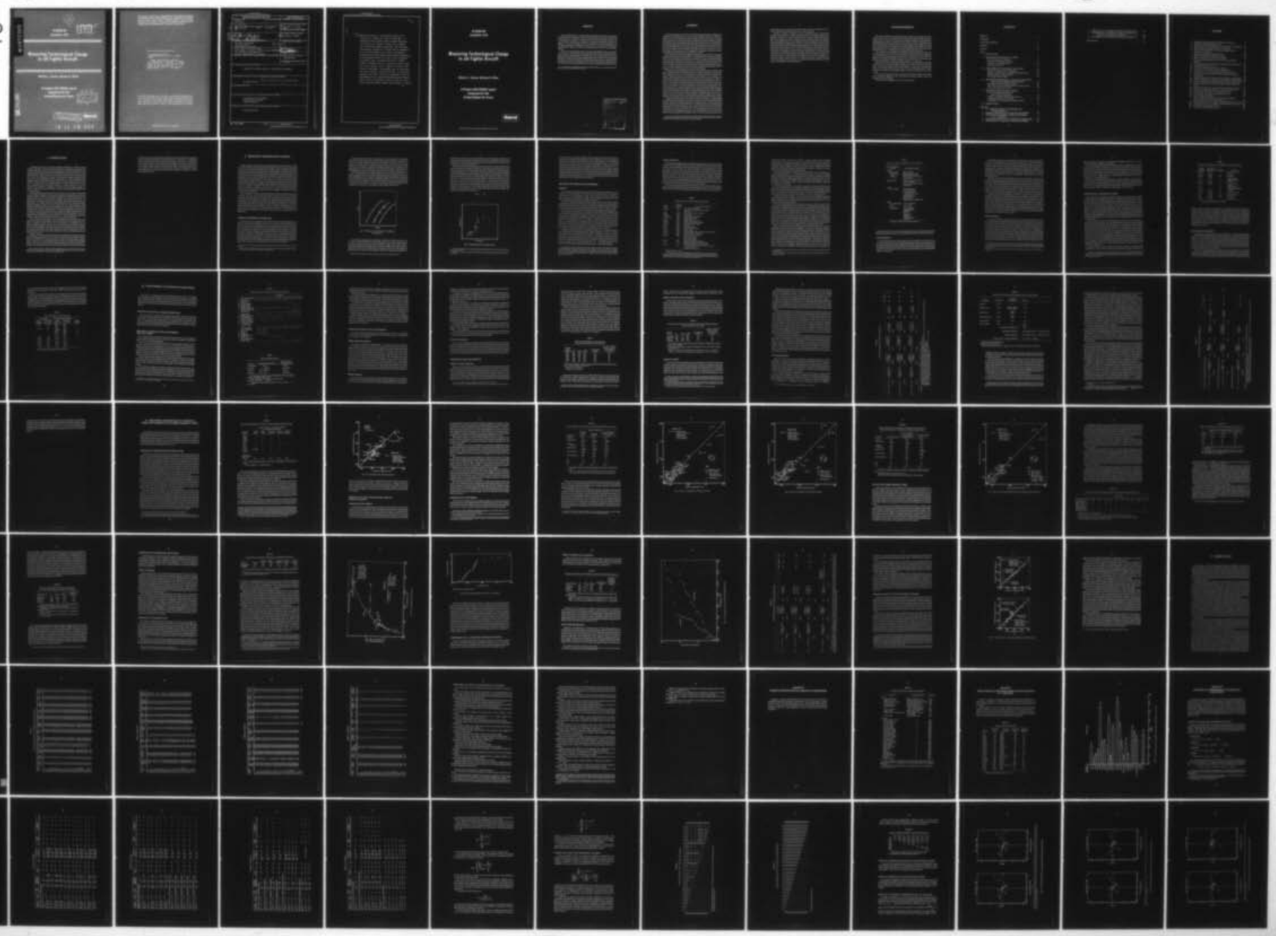

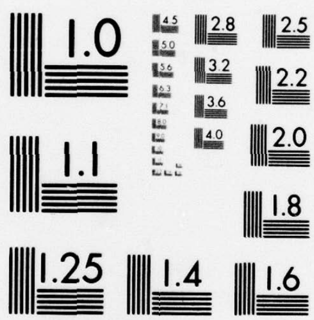

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Measuring Technological Change in Jet Fighter Aircraft

William L. Stanley, Michael D. Miller

A Project AIR FORCE report prepared for the United States Air Force

Rand
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This report

Develops technique to characterize level of and change in jet fighter air vehicle technology. It complements other methods used to assess technological risks of new fighter concepts and to compare U.S. and foreign fighter technology. The technique uses multiple regression to relate time of appearance of an aircraft design to its level of technology. Resulting expressions measure performance consequences of technological advance in terms of such parameters as specific power, sustained load factor, Breguet range, and payload fraction. Measured in these terms, the rate of advance of U.S. fighter air vehicle technology is declining. The monetary cost of increasing the rate of advance could be very high. In the future, designers will have to balance increasingly difficult improvements in air vehicle technology against improvements in other technologies (such as avionics or armament) that also enhance combat effectiveness. (Author)

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Measuring Technological Change in Jet Fighter Aircraft

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PREFACE

Previous Rand research[1] has developed a technique for measuring technological change in the development of aircraft turbine engines. This report considers the technology of the complete air vehicle, rather than just the propulsion system, and is a first effort at using such a technique to measure technological change in jet fighter aircraft. Potential applications for the technique include assessing the technological risk posed by new fighter aircraft concepts, comparing the level of technology of different fighter aircraft, and charting trends in the rate of technological advance.

This work was performed under the Project AIR FORCE project entitled *Systems Acquisition Policy Studies*. The report should be useful to development planning personnel at Headquarters United States Air Force, Headquarters Air Force Systems Command, the Aeronautical Systems Division, and the Naval Air Systems Command, as well as personnel at the Flight Dynamics Laboratory, members of the intelligence community, including those at the Air Force Foreign Technology Divison, and DoD personnel responsible for net technical assessment of fighter aircraft.

[1] A. J. Alexander and J. R. Nelson, *Measuring Technological Change: Aircraft Turbine Engines*, The Rand Corporation, R-1017-ARPA/PR, June 1972.

SUMMARY

Because satisfying a particular set of mission requirements forces designers to emphasize certain performance attributes at the expense of others, it is difficult to compare the level of technology of one jet fighter aircraft with another. Development planners who compare new fighter concepts with existing hardware to assess technological risks and intelligence personnel who compare U.S. and foreign fighter aircraft technology often face this problem. This report describes an approach that lessens those difficulties by providing a quantitative framework to characterize the level of and change in the technology of jet fighter aircraft. As used here, level of technology means the product of the application of scientific knowledge, methods, and research to the design and manufacture of aircraft.

Rand researchers earlier developed a technique for quantifying technological change in aircraft turbine engines. We have extended the development and application of this technique to the complete air vehicle.[1] To do so, we assembled design and performance information for 39 U.S. and 13 Soviet fighter aircraft, identified parameters that described the performance consequences of some important advances in fighter technology of the past 30 years, and by subjecting these parameters to multiple regression analysis developed expressions relating the time of appearance of an aircraft design to its level of technology.

The resulting expressions use parameters such as specific power, sustained load factor, Breguet range, and payload fraction to measure technology. The equation form describes the rate at which technology has advanced from the 1940s to the present. Although preliminary applications of the approach have generally provided satisfying results, several chronic problems have frustrated our efforts to improve the precision and descriptiveness of the statistical expressions. They include an unavoidably small sample of aircraft that make the equations more sensitive to the exclusion or inclusion of particular aircraft than we would prefer (particularly the F-111A); an uneven distribution of those aircraft through time (they are predominantly pre-1960 aircraft); and a multiplicity of combat roles for fighter aircraft, which makes it quite difficult to adequately describe the major attributes of each new aircraft. Nor does this formulation, developed from a data base of fighter aircraft and tailored to measure fighter attributes, satisfactorily measure the level of technology of such other aircraft types as bombers and attack aircraft.

Despite these limitations, the approach has proved useful in distinguishing between performance enhancements made possible by mission tradeoffs and those brought about by technological advance, in comparing the rate of technological advance exhibited by new and derivative aircraft, in comparing United States and Soviet fighter aircraft technology, and in evaluating the rate at which U.S. fighter technology has advanced through time and its implications for the future. For example, the results suggest that neither the United States nor the Soviet Union holds a dominant long-term advantage in basic air vehicle technology, although the

[1] The air vehicle includes the engine, airframe, and flight control system that operates as a unit to perform basic maneuvers (e.g., cruise, climb, turn, accelerate). This report does not evaluate technological trends in the development of avionics and armament systems.

United States may have enjoyed a brief advantage during the mid-1950s when U.S. Century Series fighter development activity was at its peak.

Although a constant or perhaps even an accelerating rate of technological advance characterized U.S. fighter developments of the mid-1950s, today's trend suggests a decline in the rate of improvement in basic air vehicle technology, at least when measured in terms of specific power, sustained load factor, Breguet range, and payload fraction. For example, if technical constraints, cost constraints, and external threat considerations continue to shape technology trends in the future as they have in the recent past, it might take two to five times longer to make an absolute improvement in F-15A air vehicle performance comparable to that between the F-4 and the F-15. Such a trend is not immutable; for some increase in expenditures, the military services conceivably could improve on the present rate of advance in traditional air vehicle technology. But the cost may be high, and the services will have to make carefully calculated choices between investing in increasingly difficult improvements in air vehicle technology or improvements in other technologies (such as avionics or armament) that may provide an easier avenue for enhancing combat effectiveness.

ACKNOWLEDGMENTS

This work profited from the suggestions and contributions of fighter airframe manufacturers, Air Force personnel, and fellow Rand staff members. Renso L. Caporali and his staff at the Grumman Aerospace Corporation provided many useful suggestions for the preparation of the report, as did R. A. Eberhard of the McDonnell Aircraft Company. John Patierno and others at the Northrop Corporation, Aircraft Division, commented on an early briefing on this subject, as did Ed Schnakenburg at the Los Angeles Aircraft Division of Rockwell International, and Ben R. Rich and C. L. Johnson of the Lockheed-California Company.

The Aerodynamics and Performance Branch of the Directorate of Flight Systems Engineering of the Air Force Aeronautical Systems Division provided data and also reviewed an early draft of this report. H. F. Stump, H. J. Kuns, and E. A. Macha of the Foreign Technology Division of the Air Force Systems Command also provided consultation on relevant subjects covered in the analysis.

Rand staff members Giles Smith, Robert Perry, and Jean Gebman provided guidance and constructive criticism throughout the course of the research. William Krase served as an informal technical reviewer on a very early version of the report. John Rolph, Winston Chow, Joseph Hall, and William Rogers of Rand's statistical consulting group suggested ways to check the statistical rigor of the results.

In reviewing the final draft, Arthur Alexander and Thomas Kirkwood of Rand made numerous suggestions that improved the technical quality, logic, and presentation of the findings.

The authors are responsible for any remaining errors.

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I. INTRODUCTION

To assess the level of air vehicle technology embodied in a fighter aircraft, analysts frequently evaluate individual technical or performance characteristics and then rank them in importance by applying their own value system. That value system is often shaped by the individual performance achievements that have been demonstrated by other aircraft (e.g., the speed of the YF-12, the maneuverability of the F-16). But unless similar mission requirements influenced the design of all the aircraft in the comparisons, this kind of approach can yield misleading results; designers often trade off performance in one area (e.g., range) for better performance in another area (e.g., maneuverability) to satisfy a particular set of mission requirements. The measurement problem is compounded when one tries to measure and compare the capabilities of nations to develop fighter aircraft, because one must consider many different aircraft models designed to different mission requirements.

This report documents an exploratory attempt to overcome some of these difficulties through development of an alternative approach to measure the level of and change in basic air vehicle technology through time.[1] Earlier Rand research on technological change in aircraft turbine engines provided the framework and stimulus for the present work.[1-3] Our technique uses conventional measures of performance (e.g., range, load factor) to describe the level of air vehicle technology. Multiple regression relates the time of appearance of an aircraft design to these measures of technology. The resulting equations provide an analytic framework for comparing the levels of technology that characterize different aircraft and for charting the rate of technological advance through time. Measuring trends through simultaneous consideration of the multiparameter tradeoffs imposed by the development process distinguishes this technique from other analyses that separately consider trends in each performance area (e.g., in maximum speed).

In the context of this study, level of technology means the product of the application of scientific knowledge, methods, and research to the design and manufacture of fighter aircraft. The key word is application, for designers may not always immediately apply advances in the state of the art (the limits of scientific and technical knowledge) to increase the level of technology of the next airplane. The analysis described in this report deals strictly with the application topic by measuring the level of and changes in technology. It does not address measurement of the state of the art.

Section II explains the general approach and describes the rationale used to select technology parameters, a time index for measuring technological change, and the data base of U.S. aircraft. Section III details the step-by-step procedures used to obtain the U.S. technology equations. Section IV compares technological growth in new and derivative aircraft, evaluates the sensitivity of the approach to changes in the composition of the data sample, and considers whether the approach

[1] The air vehicle includes the engine, airframe, and flight control system that operates as a unit to perform basic maneuvers (e.g., cruise, climb, turn, accelerate). This report does not evaluate technological trends in the development of avionics and armament systems.

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developed to measure jet fighter technology growth can satisfactorily measure the level of technology of bombers and attack aircraft. In Section V we distinguish between mission tradeoffs and absolute performance improvement in fighter aircraft, assess changes in technological trends through time and their implications for the future, and compare U.S. and Soviet jet fighter technology trends. Section VI concludes with some observations about the utility of the approach and possible refinements or extensions. Eight technical appendixes support the observations made in the text.

II. MEASURING TECHNOLOGICAL CHANGE [1]

Modern fighter aircraft incorporate design features that permit them to fly at over twice the speed of sound, sustain high-load-factor turns at supersonic speeds, and carry heavy payloads long distances in subsonic flight. Designers are prone to cite particular aircraft innovations (such as swing wings) or improvements (such as lighter structure) or the performance made possible by the innovations or improvements (such as higher speeds and load factors) in characterizing the level of technology of a particular aircraft. But one can be misled when comparing one nation's aircraft with another's in such terms, or even when rating one national aircraft against another. To provide a particular set of features, or satisfy a specified mission requirement, designers must emphasize certain performance attributes at the expense of others. Those who wish to make comparisons between aircraft must decide subjectively which are the "most important" performance features and then assess how much one aircraft surpasses or is inferior to another in terms of those features.

Such a subjective evaluation often leads to gross characterizations: The aircraft is ahead of its time, the aircraft lags behind the state of the art, the aircraft represents a breakthrough in technology. Here we are trying to provide a quantitative framework that satisfies our intuitive understanding of the meaning of the terminology while imposing a discipline on subjective evaluations. Our approach represents an exploratory attempt to develop a tractable, objective means of measuring technological change in fighter aircraft. It would be presumptuous of us to assume that our approach is in all circumstances superior to all other methods of assessing levels of technology. The most that we can expect is to complement other approaches.

GENERAL STATEMENT OF APPROACH

We begin with the assumption that a limited number of parameters can describe the important technological features of an aircraft.[2] The development process acts on this set of parameters over time, increasing its value to bring about what is defined here as technological change. Second, we must be able to use one set of parameters to describe the many changing technical qualities of fighter aircraft over time. For example, a performance parameter such as maximum speed can measure aspects of technological advance even if a fundamental change in propulsion technology permitted the increases in speed. The transition from reciprocating engines to jet propulsion is a case in point. The assumption of continuity also requires that new development begin where previous development ends (having reached a given level of technology, one never has to reattain it).

[1] We reiterate theoretical concepts originally introduced in Ref. [1] to maintain continuity in the discussion.

[2] In Sec. III we will consider the extent to which assigning many different combat roles to fighters makes it difficult to assemble a comprehensive parameter set.

The parameters that describe a technology can be divided into two dependent (sometimes overlapping) subsets: performance-oriented parameters valued by the user (such as speed, sustained load factor) that define the ability of an aircraft to perform a specified mission, and technical parameters (such as skin friction drag, maximum lift coefficient, longitudinal stability margin) that the designer may manipulate to provide a desired set of performance attributes. Because of their interdependence, we can concentrate on just one of the subsets of parameters.

An aircraft designer can make trades among the various performance and technical qualities in order to satisfy different performance objectives. For example, as suggested in Fig. 1, at time t_1, the designer might trade off weight and power[3] to satisfy the performance objectives defined by points A, B, and C on the tradeoff curve. In reality, the designer rarely has the considerable latitude suggested by Fig. 1. Rather he must operate in a world of constraints, including (for instance) the availability of only one or two engines having suitable thrust levels.

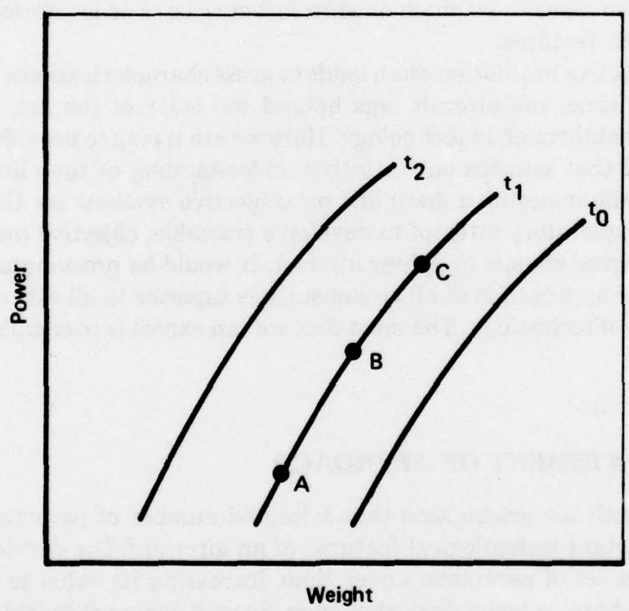

Fig. 1—Technology tradeoff surface for different time periods

As technology progresses, the technology tradeoff curve shifts (e.g., from t_1 to t_2 in Fig. 1) and the aircraft can develop more power for a given weight because of airframe and engine improvements. But different mission objectives, the technical approaches of various manufacturers, interservice differences in design requirements, the availability of suitable engines, and other factors will cause a scatter of power values for a given level of technology. Therefore a technology tradeoff curve

[3] Represented by the product of thrust and maximum velocity, in appropriate units.

generated by a statistical analysis will differ from the well-defined tradeoff curves typical of a detailed parametric engineering analysis of a single fighter concept. The statistically derived technology tradeoff curve represents the actual choices and realities of the development process.

Historical trends in individual performance parameters reflect tradeoffs made along a particular technology tradeoff curve and temporal improvements in technology represented by movement from one curve to another. Consequently there is a considerable scatter in values. Figure 2 illustrates the trend in power developed per pound of jet fighter weight. Although examination of such trends can yield some limited insights about how one aircraft ranks with respect to another, in the absence of any all-encompassing technological figure of merit for jet fighter aircraft, adequate characterization of technology requires a multiparameter tradeoff surface. We can estimate the shape and movement of such a surface using multiple regression[4] if the shape of the surface does not change over time and its movement is regular.[5] The movement of the surface represents technological change. The function describing this surface for jet fighter aircraft, which we will statistically estimate in Section III, has the form:

$$t = f(P_1, \ldots, P_n)$$

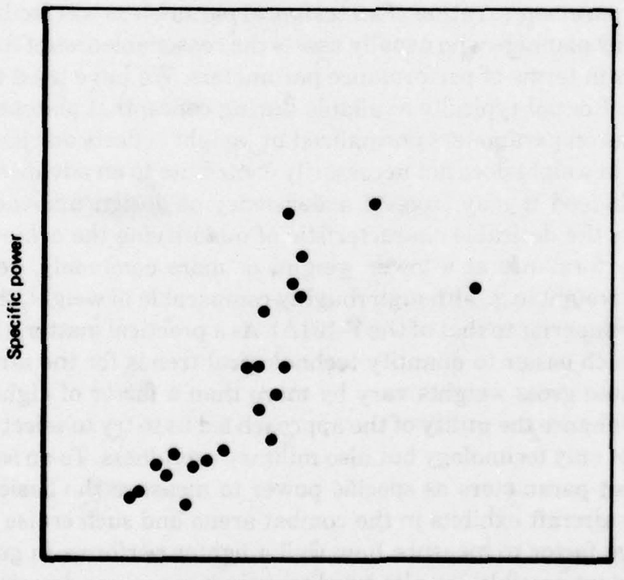

Fig. 2—Single parameter technology trend

[4] The statistical technique of multiple regression determines the curve or surface that best fits a sample of observations.

[5] "Regular," in this context, means that a smooth function describes the movement of the surface through time.

with t the time a particular jet fighter aircraft appeared, and the Ps the set of n performance parameters describing the level of technology of the aircraft. Specification of the equation's functional form and a determination of its coefficients provide a way to measure the average rate of technological advance over time. We can assess the technical risk of a prospective program by comparing the rate of advance required to satisfy program goals with the typical rate of advance quantified by the equation. To do so, we insert the parameter values describing a fighter aircraft concept into the equation, obtaining a calculated time of appearance. If the schedule expectation of the service or the contractor is significantly earlier than the calculated time of appearance, then one might prudently ask whether the technological goals of the program are too ambitious.

SELECTION OF TECHNOLOGY PARAMETERS

Rationale

Four considerations influenced the selection of technology parameters: (1) concentration on the technology of the flight vehicle itself and not on its avionics or armament, (2) use of performance rather than technical parameters, (3) primary use of parameters normalized by weight, and (4) emphasis on parameters that characterized both technology and military usefulness.

The first consideration simply reflects the scope of the analysis. The emphasis on performance parameters rather than technical parameters will facilitate the use of the approach by planners who usually assess the reasonableness of future fighter aircraft concepts in terms of performance parameters. We have tried to tailor our set to the level of detail typically available during conceptual planning stages.

The emphasis on parameters normalized by weight reflects our judgment that a mere increase in weight does not necessarily contribute to an advance in the level of technology. Indeed it may suggest a deficiency of design innovation.[6] These parameters have the desirable characteristic of quantifying the achievement of a fixed level of performance at a lower weight, or more commonly, better performance at a fixed weight (e.g., although roughly comparable in weight, the F-15A has performance far superior to that of the F-101A). As a practical matter, these parameters made it much easier to quantify technological trends for the aircraft in our data sample whose gross weights vary by more than a factor of eight.

A desire to enhance the utility of the approach led us to try to select parameters that reflected not only technology but also military usefulness. To do so, we considered such combat parameters as specific power to measure the basic air vehicle performance an aircraft exhibits in the combat arena and such cruise parameters as Breguet range factor to measure how well a fighter performs in getting to the arena. To the extent possible, we also tried to include measures descriptive of both air-to-air capability (e.g., sustained load factor) and air-to-ground capability (e.g., payload fraction), because many fighters must perform multiple functions.

[6] A structural scaling relationship, the so-called "square/cube law", does suggest a modestly increasing structural weight fraction with size, which means a designer does have to overcome certain constraints to maintain performance when building a larger aircraft. After reviewing Ref. [4], we estimated that this scaling law would have a modest effect on aircraft of fighter size; hence, we used parameters normalized by weight as much as possible because of their considerable advantages.

Combat Parameters

The historical perspective shown in Table 1 lends credence to the assertion that, at least until the mid-1960s, the quest for higher speeds has accounted for a number of major technological innovations in fighter aircraft vehicles. Recognition that the jet engine could overcome the speed limitation of propeller-driven aircraft prompted the fundamental change to jet propulsion. But increased speeds caused shock waves to form over wings, tail surfaces, and airframe projections. Exploiting scientific advances in both the United States and Germany, American designers after World War II swept the wings and tail surfaces of the F-86A and the F7U-3 to delay the onset of compressibility and permit higher speeds. Concurrently, the incorporation of afterburners on the F6U-1 and F-94A operational fighters provided short bursts of power that permitted even greater speeds.

Other concepts explored and developed during the late 1940s and 1950s to allow higher speeds included the delta wing, first used operationally on the Navy's F4D-1 and the Air Force's F-102A. Designers first applied the area rule principle to an

Table 1

MILESTONES IN U.S. JET FIGHTER DEVELOPMENT[a]

Model	Year of First Flight	Innovation/Achievement
P-59A	1943	First American jet fighter
F-80A	1944	First true operationally useful jet fighter Side inlets
FH-1	1946	First operational Navy jet fighter
F-86A	1948	Swept wing
YF-92A	1948	Powered delta wing aircraft
F6U-1/F-94A	1949	Afterburning turbojets
F-86E	1950	Leading-edge slats
F-84G	1951	Inflight refueling capability
XF10F-1	1951	Experimental swing wing fighter
F-100A	1953	Sustained supersonic flight
F4D-1	1954	Delta wing
F11F-1	1954	Area ruled fuselage
F-8A	1955	Variable incidence wing
F-104A	1956	Mach 2+ speed
F-4A	1958	Two dimensional engine inlet with movable ramps
YF-12A	1962	Sustained Mach 3+ prototype
F-5A	1963	Leading edge wing extension
F-111A	1967	Mach 1.2 at sea level Afterburning turbofans Variable sweep wing
F-14A	1970	Automatic variable sweep wing
F-16A	1976	Relaxed static stability control system Full primary analog fly-by-wire control
F-18A	1978	Composites account for greater than 20 percent of structural weight Digital fly-by-wire control

SOURCE: Refs. [5] to [8].

[a]For production aircraft in this listing the model designation and first flight date reflect aircraft procured in quantity that became operational. Experimental, prototype, or limited production versions of the aircraft may have demonstrated performance attributes somewhat earlier. We discuss this classification problem below.

operational aircraft in the Navy's F11F-1 to reduce transonic drag. As speeds reached Mach 2 and beyond, Lockheed incorporated shock control cones and a bleed system on the F-104A's air intakes to tailor the airflow to the engine. The push for higher speeds for fighter aircraft culminated in the early 1960s in the YF-12A prototype, which demonstrated a sustained cruise capability at speeds in excess of Mach 3 using continuous afterburning engines.

The historical emphasis on speed led to consideration of the maximum sustained speed capability as a combat parameter choice to measure technology growth (see Table 2). Because this parameter does not directly quantify the technology associated with packaging high speed in a small, lightweight vehicle, we also considered specific power.[7] Gabrielli and Von Karman successfully used this parameter in the landmark paper, "What Price Speed—Specific Power Required for Propulsion of Vehicles."

Combat ceiling provides one means for measuring altitude performance. The maximum specific energy,[8] an important parameter in energy-maneuverability theory, collectively describes the speed and altitude performance of fighter aircraft. Providing a measure of acceleration capability, sea-level rate of climb indicates the specific excess power an aircraft has available to climb or change velocity.

Historically, maneuverability has not received as much emphasis as speed in the development of U.S. jet fighter aircraft. Designers have sometimes sacrificed good maneuverability to enhance performance in other mission areas (e.g., air-to-ground weapon-carrying capability).

During the development of the Century fighter series (F-100 through F-107), reliance on air vehicle maneuvering capability in combination with guns as armament shifted toward greater reliance on air-to-air rockets and missiles. Perhaps partly as a result of Vietnam combat experience, the trend has again changed. Transonic maneuverability was an important design consideration in the development of the F-15A and the F-16A as well as the Navy's F-14A. Because most jet fighter aircraft turn best at high subsonic speeds, we selected the maximum sustained load factor achievable at a representative flight condition of Mach .8 at an altitude of 25,000 feet to characterize aircraft maneuverability. Although thrust-to-weight ratio and wing loading are not direct measures of military usefulness, they also indicate an aircraft's maneuver potential, so we evaluated them as well.

Many other maneuver parameters seemed potentially attractive; however, definitional problems and the unavailability of data for an adequate sample of aircraft prevented the formulation and testing of alternative parameters. For example, definitions of maximum usable lift coefficient were inconsistent from aircraft to aircraft, making it extremely difficult to test reliably for the significance of the maximum instantaneous load factor. This parameter might also have measured certain improvements in aircraft handling characteristics. A persistence parameter that measures the length of time an aircraft can engage in maneuvering combat also seems desirable for measuring turning capability, fuel consumption, and fuel capacity. The point performance parameter selection (Mach .8 at 25,000 feet) does not quantify the capability of contemporary fighter aircraft to perform sus-

[7] The product of maximum thrust and velocity divided by vehicle weight. (See Appendix A for complete definitions.)

[8] The maximum sum of the specific kinetic and potential energy an aircraft can attain in its 1g altitude-speed envelope.

Table 2

TECHNOLOGY PARAMETERS TESTED FOR U.S. AIRCRAFT

General Performance Attributes	Technology Parameter[a]
Combat	
Speed, altitude performance, energy, acceleration	Maximum speed Maximum specific power Maximum specific energy Maximum climb rate (sea level) Combat ceiling
Maneuverability	Maximum sustained load factor (M= .8, h=25 kft) Thrust-to-weight ratio (sea level) Wing loading
Cruise	
Range, payload	Breguet range factor Internal fuel fraction Total fuel fraction (internal and external) Payload fraction Useful load fraction Breguet range Payload fraction x Breguet range
Other	
Structural strength	Structural efficiency
Weight	Empty weight
Miscellaneous	Carrier capability Variable geometry Speed class Mission Manufacturer Design lag Design antecedent Design class

[a]Appendix A formally defines these parameters.

tained high load factor turns at supersonic speeds. Using the integrated area of the maneuvering flight envelope as a parameter might overcome this shortcoming.

Cruise Parameters

We assembled parameters that measure how far a fighter aircraft can fly and how much payload it can carry. Mission application has had a strong influence on the range and payload capability designed into fighter aircraft. For example, early jet fighters designed for the bomber escort mission had high fuel fractions and good range factors, but designers usually traded off range performance for climb performance in interceptors.

The Breguet range factor quantifies several important trends in cruise performance in the development of U.S. jet fighter aircraft.[9] As maximum speeds have increased wing aspect ratios have decreased, yielding higher subsonic cruise speeds, but also lower cruise lift-to-drag ratios that adversely affect range performance.[10] Improvements in engine technology, including the introduction of turbofans, have significantly improved the specific fuel consumption characteristics of contemporary engines, increasing range. Thus, the range factor captures some of the fundamental changes that have occurred in aerodynamic and propulsion technology through the years.

Although the range factor describes how well an aircraft can translate fuel energy into range, some measure of the quantity of on-board fuel is also desirable. Several normalized parameters describe the internal and external fuel capacity of an aircraft. We computed the internal fuel fraction, defined in this analysis as the ratio of the internal fuel weight to the airplane weight with zero fuel. Most fighter aircraft can also carry substantial quantities of fuel in external tanks, so we computed a total fuel fraction, the ratio of the weight of the maximum fuel load (internal and external) to the weight of the aircraft with all fuel tanks drained.

To measure the payload capability of a fighter, we computed a nondimensional payload-to-weight ratio (or payload fraction) represented by the difference in the maximum gross weight and the weight with full internal fuel divided by the maximum gross weight. The useful load fraction parameter, represented by the difference in the maximum gross weight and the empty weight divided by the maximum gross weight, provides a gross measure of an aircraft's ability to carry fuel and payload. Using the Breguet range equation, we computed aircraft range on internal fuel at the maximum gross weight loading condition. We also evaluated the product of payload fraction and range as a crude measure of the integrated range-payload performance normalized by gross weight.

Other Parameters

To quantify possible economies in the use of aircraft structure that may have occurred through the years because of improvements in design techniques, materials, and fabrication techniques, we defined a gross structural efficiency parameter as the ratio of the structural weight to the product of the ultimate load factor and stress design weight. A decrease in this parameter represents technological improvement, although historically we would not expect to observe a consistent declining trend in the value of this parameter because designers have used technological advances to build the more complex structures necessary for supersonic flight without increasing weight. The inclusion of speed-related parameters in the multivariable regression should control for this obscuring effect. Because achieving a particular level of performance at a lower weight than another aircraft with the

[9] The Breguet range factor, the maximum product of the cruise speed and lift-to-drag ratio divided by the specific fuel consumption, measures how well fuel energy is translated into range by the propulsion system and aerodynamic performance of an aircraft. (See Ref. [10] for a derivation of the Breguet range equation.)

[10] The variable sweep wings of the F-14A and F-111A represent one approach to circumventing the problem.

same performance could also be considered technological improvement, we also used vehicle empty weight as a parameter.

Other, less easily quantifiable factors, grouped under "miscellaneous" in Table 2, may also contribute to describing a given level of technology. For example, a hypothetical Navy fighter aircraft with performance equivalent to that of an Air Force aircraft but also able to operate from an aircraft carrier, may represent a higher level of technology. To deliver equivalent performance the Navy vehicle must overcome the weight penalty that attends carrier operations.[11] The carrier capability variable recognizes this.

Similarly, we identified variable geometry aircraft, subsonic aircraft, and aircraft having a primary air-to-ground mission orientation. We also tested for differences in the level of technology achieved by various airframe manufacturers. The motivation for testing the last three so-called design variables shown in Table 2 will become apparent when we discuss the composition of the data base.

SELECTION OF A TECHNOLOGY INDEX

The performance parameters of Table 2 represent the independent variable candidates for the technology equation. To complete the parameter set, we had to choose a dependent variable indicating the time when a particular level of technology had been reached. Several benchmarks seemed potentially appropriate, including the date of the first flight, the date of the initial operational delivery to the services, or Initial Operational Capability (IOC), which usually occurs after the delivery of a squadron (approximately 24 aircraft). We selected the date of first flight for use as the technology index because it provides the least ambiguous, however imperfect, measure of the time when a basic package of air vehicle technology has been assembled. In contrast, the last two operational milestones seemed less clearly identifiable and more dependent on arbitrary definitions by the developing services.

If the military services all developed fighter aircraft in the same manner, progressing through discrete and well-defined experimental, prototype, development, and production phases, then the selection of an appropriate and consistent first flight date would not pose much difficulty. An examination of Table 3 clearly illustrates that this has not been the case; hence, we had to make some subjective decisions about first flight dates. We usually used the first flight dates of development test aircraft because they generally establish basic air vehicle performance and include most of the fully engineered systems for the production vehicle. Two aircraft in our sample progressed only to the prototype stage (XF10F-1 and YF-107A), so we had no choice of first flight dates. The F-4A was a development aircraft, but a subsequent version, the F-4B, incorporated a number of important design changes and also was the first in the F-4 series procured in sizable numbers, so we used its first flight date.

Because we had to make subjective decisions to identify an appropriate first flight date for some aircraft in the sample, we defined two design variables intro-

[11] Simplified controls and deletion of the wing fold, arrestor gear, and catapulting strong points will reportedly save over 3600 pounds on the land-based F-18L Cobra version of the Navy's new F-18 Hornet fighter. George Farrow, "Combat Aircraft Design Analysis No. 2—McDonnell-Douglas/Northrop F-18," *Interavia*, July 1978, p. 608.

Table 3

EXAMPLES OF FIRST FLIGHT DATE SELECTION FOR U.S. AIRCRAFT

Model Designation	First Flight Date (FFD)	Number Built	Comments
XF10F-1	5/1951	2	Unambiguous FFD[a]
YF-100A	5/1953	2	Prototype
F-100A	10/1953	203	FFD used[a]
XF-88	10/1948	2	Early penetration fighter prototype
F-101A	9/1954	77	FFD used[a]
XF-104	2/1954	2	First experimental version
F-104?	?	17	Experimental configuration test aircraft
F-104A	2/1956	153	FFD used[a]
YF-107A	9/1956	3	Unambiguous FFD[a]
F-4A	5/1958	47	First in F-4 series
F-4B	3/1961	649	FFD used[a]
F-14A	12/1970	?	Unambiguous[a]

[a]The model and date used in the analysis.

duced in Table 2 to explore the sensitivity of first flight date to the existence of previous flight hardware (experimental or otherwise). We defined a design lag variable that measured the time between flight of an aircraft in our sample and flight of its earliest design antecedent (e.g., 71 months between flight of the XF-88 and the F-101A), and a design antecedent dummy variable that merely identified the existence of previous flight hardware. Appendix A documents all the first flight date selections used in the analysis, and Appendix C tabulates the design lag between flight of predecessor experimental or prototype aircraft and subsequent development aircraft.

DATA BASE OF AIRCRAFT

We assembled technology parameters for the 39 Navy and Air Force jet fighters shown in Table 4 whose development spans a 30-year time period from the first flight of the Navy's FH-1 in 1946 to the first flight of the F-16A in 1976. Because we had more interest in the operational application of technology than in its experimental derivation, the aircraft we selected for the data base are primarily, but not exclusively, fighter aircraft models ultimately used by the services for purposes other than testing: that is, we are interested in the performance demonstrated by the F-104A rather than by the XF-104.

There is no rigorous definition of a fighter aircraft that might serve as a guide for including or excluding aircraft from the data base, although we can draw some distinctions among fighters, bombers, and attack aircraft. Mission requirements for the latter two types of aircraft generally place more emphasis on range and payload

Table 4

U.S. JET FIGHTER AIRCRAFT IN THE DATA BASE

New Design		Derivative (Growth) Designs	
Model Designation	First Flight Date	Model Designation	First Flight Date
FH-1	1946	F2H-1	1948
FJ-1	1947	F-86D	1949
F9F-2	1948	YF-93A	1950
F-86A	1948	F-89C	1951
F-94A	1949	F-94C	1951
F3D-1	1950	F2H-3	1952
F-89A	1950	F-84F	1952
XF10F-1	1951	F-86H	1953
F9F-6	1952	FJ-3	1953
F-100A	1953	FJ-4	1955
F4D-1	1954	F5D-1	1956
F11F-1	1954	F-104G	1960
F-101A	1954	F-4C	1963
F3H-2	1955	F-5A	1963
F-102A	1955		
F-8A	1955		
F-104A	1956		
F-105B	1956		
YF-107A	1956		
F-106A	1956		
F-4B	1961		
F-111A	1967		
F-14A	1970		
F-15A	1972		
F-16A	1976		

	Design		
Service	New	Derivative	Total
Air Force	13	9	22
Navy	12	5	17
Total	25	14	39

performance than do fighter requirements. Many attack aircraft have not incorporated afterburners because mission requirements did not demand their thrust increment. Bombers usually have a much lower design limit load factor than fighter aircraft, and that has a manifest influence on the design and weight of the fighter airframe. We have limited our data sample to aircraft designated by the military services as fighters, but we have also made a preliminary assessment in Sec. IV of whether the approach, as developed for fighter aircraft, can satisfactorily measure the level of technology of attack aircraft and bombers.

The data base reflects the uneven development history of U.S. fighter aircraft (see Fig. 3). The concentration of aircraft in the 1940s and 1950s (80 percent of the new design aircraft) posed some analytic difficulties in establishing reasonable trends for contemporary fighter aircraft. We tested a weighting scheme (described in Sec. IV) in an attempt to compensate for the uneven distribution of aircraft.

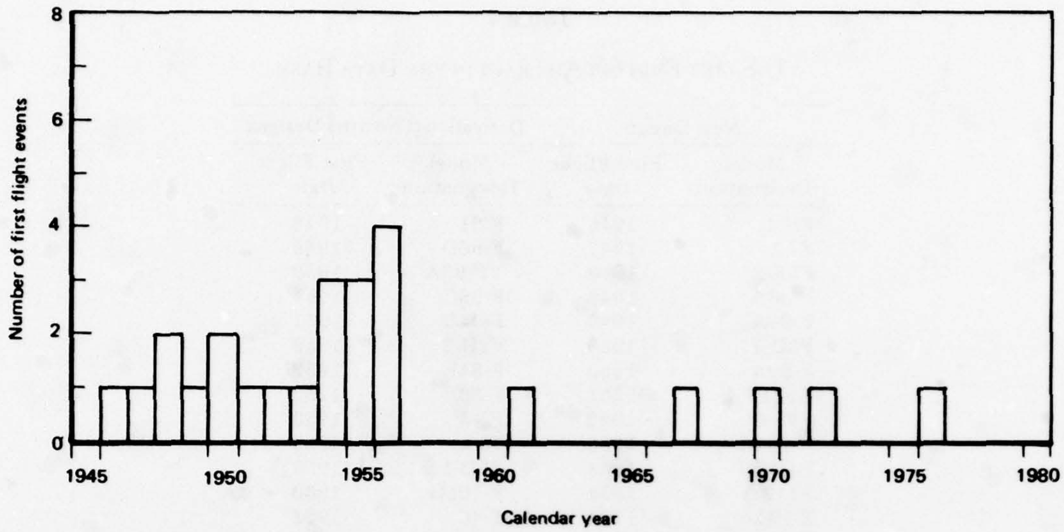

Fig. 3—Distribution of first flight events for new designs in data base

The data base includes most, but not all, of the new operational fighter models introduced in the United States since the 1940s. Early aircraft not included because of data unavailability include the P-80A, F-84B, F6U-1, and F7U-3. This presented no real difficulties, because the data base still includes many aircraft developed in the late 1940s and early 1950s. It does not include the YF-12A Mach 3 fighter prototype, which first flew in 1962. Even if it did include all the aircraft of interest, the data base would still be considered small for purposes of statistical analysis.

The data base has only three swing-wing fighters (the prototype Grumman XF10F-1 Jaguar, the F-111A, and the F-14A) and includes no VSTOL aircraft.[12] Moreover, only three of the aircraft classified as new designs in the data base (the F-105B, YF-107A, and F-111A) had a predominant air-to-ground mission orientation early in their development cycle. Hence, the technology tradeoffs for fixed geometry, conventional takeoff and landing aircraft with an air-to-air mission orientation dominate the statistical results of Sec. III.

We disaggregated the data base by distinguishing between new designs and derivative or growth versions of existing aircraft. This naming convention reflects an effort to ensure the inclusion in the new design category of aircraft incorporating significant design innovations or demonstrating superior performance during a particular time. This factor weighed more heavily in the delineation of new and derivative designs than the lineage of flight hardware of a particular aircraft. In some cases, we could make clear and unambiguous classifications (e.g., the F-15A was a new design, the F-89C was a derivative design). In other cases, we had to make subjective judgments to classify the aircraft. For example, although the F-102A program laid the groundwork for the F-106A, we classified the F-106A as a new design in the data base because, in contrast to the F-102A, it had a new engine, relocated air intakes, variable geometry inlets, a modified vertical stabiliz-

[12] Vertical or short takeoff and landing.

er, and markedly better performance. We classified the F-5A as a derivative design because of the long history of T-38 and N-156C development that preceded its production.

Overall, we classified 25 aircraft as new designs and 14 as derivative designs. When dealing with the entire sample of new and derivative aircraft, we used the "design class" variable introduced in Table 2 to distinguish between the two aircraft types. Seven aircraft classified as new designs have one or more corresponding derivative designs in the data base (see Table 5). We used this latter set of paired new and derivative aircraft in Sec. IV to examine the technological growth exhibited by derivative designs.

Table 5

NEW AND DERIVATIVE FIGHTER PAIRS

New Designs		Derivative (Growth) Designs		
Model Designation	First Flight Date (Year)	Model Designation	First Flight Date (year)	Engine Change[a]
FH-1	1946	F2H-1	1948	x
		F2H-3	1952	x
F-86A	1948	F-86D	1949	
		YF-93A	1950	x
		F-86H	1953	x
		FJ-3	1953	x
		FJ-4	1955	x
F-94A	1949	F-94C	1951	x
F-89A	1950	F-89C	1951	
F4D-1	1954	F5D-1	1956	
F-104A	1956	F-104G	1960	
F-4B	1961	F-4C	1963	

[a]New engine model installed in derivative aircraft.

III. DEVELOPMENT OF TECHNOLOGY EQUATIONS

To arrive at a desirable set of technology equations for the 25 U.S. fighter aircraft classified as new designs, we had to select logical groupings of variables to test, consider alternative functional equation forms, and develop an engineering and statistical rationale for evaluating the attractiveness of the various equations.[1] This section describes that process and the equations obtained as a product of that process.

SELECTION OF LOGICAL VARIABLE GROUPINGS

To develop the U.S. technology equations, we generally used the parameters introduced in Table 2. From this list, we selected variable sets that always included two combat variables describing speed and maneuverability performance, two cruise variables describing range and payload performance, and other variables describing particular design or mission characteristics. Table 6 depicts the major groupings of variables used in the analysis.

SELECTION AND IMPLICATIONS OF DIFFERENT EQUATION FORMS

We considered four alternative functional equation forms in the development of the technology equations. Shown in Table 7, each form has different implications about the rate of technology change.

One or more of these forms may describe the various growth phases a technology may experience. For example, an "S" curve of technology development includes a period of slow constant growth, an acceleration phase of rapid growth, and a deceleration phase as it becomes progressively more difficult to sustain the previous rapid growth. To the extent possible with such a small data base, we will later describe our efforts to determine whether the evidence suggests jet fighter technology has undergone more than one characteristic growth phase.

The first equation form implies that a constant absolute change in performance will always yield the same absolute change in the dependent variable, first flight date. Although it seems unreasonable to expect that most technologies could grow in this manner indefinitely, the form could describe certain phases of technology growth.

The second form implies that a constant percentage change in performance will always yield the same absolute change in first flight date. Of course, as technology advances, that constant percentage change in performance represents greater and greater absolute gains in performance (e.g., going from a load factor of 4 gs to 4.4 gs compared with going from 8 gs to 8.8 gs); hence the equation form implies an

[1] Except for a sensitivity analysis that considered the inclusion of derivative aircraft, we dealt exclusively with the sample of new designs.

Table 6

Major Groupings of Technology Parameters Tested

	Technology Parameters	Groupings 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Specific power	x	x	x	x	x	x	x	x	x	x	x					x
C	Climb rate												x				
O	Specific energy													x			
M	Maximum speed														x	x	
B	Combat ceiling															x	
A	Sustained load factor	x	x	x	x	x	x	x	x	x	x	x	x	x			x
T	Thrust-to-weight ratio														x	x	
	Wing loading														x	x	
	Breguet range	x				x			x				x	x	x	x	x
C	Breguet range factor		x	x	x		x	x		x	x						
R	Payload fraction	x				x			x				x	x	x	x	x
U	Internal fuel fraction		x				x			x							
I	Total fuel fraction			x				x			x						
S	Useful load fraction				x												
E	Payload fraction x Breguet range											x					
	Carrier capability	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Variable geometry	x	x	x	x												
O	Speed class	x	x	x	x												
T	Mission	x	x	x	x												
H	Design lag	x	x	x	x												
E	Design antecedent					x	x	x									
R	Design class								x	x	x						
	Structural efficiency																x
	Empty weight														x	x	

Table 7

Equation Forms Tested

Form	Functional Representation[a]	Implied Rate of Technology Change
Linear-linear[b]	$t = f(P_i)$	Constant
Linear-log[c]	$t = f[\ell n(P_i)]$	Acceleration
Log-log[c]	$\ell n(t) = f[\ell n(P_i)]$	Depends
Log-linear[b]	$\ell n(t) = f(P_i)$	Deceleration

[a]The dependent variable t is the first flight date. The P_i's describe design or performance characteristics.

[b]More specifically, the function f takes the form $f(P_i) = b_0 + b_1 \times P_1 + \ldots + b_n \times P_n$.

[c]The function f takes the form $f[\ell n(P_i)] = b_0 + b_1 \times \ell n(P_1) + \ldots + b_n \times \ell n(P_n)$.

acceleration in technology. Again, it seems unreasonable to expect that most technologies could follow this course indefinitely, although many probably experience an acceleration phase.

The third equation form implies that a constant percentage change in performance yields a constant percentage change in first flight date. Whether the equation represents a deceleration or acceleration in technology depends on the value of the coefficients of the logarithmic terms containing the independent variables.

The fourth form implies that a constant absolute change in performance yields a constant percentage change in first flight date. As technology advances, the value of the performance parameter set increases, and the dependent variable also increases. The equation then implies that the same absolute increase in performance will require more time as technology advances—a deceleration in technology. As many technologies mature, we would expect them to experience such a phase.

Which equation form best describes technology growth in U.S. jet fighters? Whatever trend applies could have important implications in acquisition planning for future jet fighters. To answer the question, we evaluated the four equation forms by considering the accuracy of the resulting regression expressions and the patterns of their residuals.

RATIONALE USED TO EVALUATE RESULTS

To evaluate the technology equations obtained in the analysis, we considered their intuitive engineering reasonableness, their statistical quality, and the predictive properties they exhibited.

Engineering Reasonableness

To evaluate engineering reasonableness, we considered whether the parameters identified as significant by means of the statistical analysis were generally consistent with the historical perspective on fighter technology emphasis (described in Sec. II). We rejected equations having coefficients with signs that did not agree with our notions about advances in technology (e.g., a sustained load factor coefficient should have a positive sign because, all other things being equal, an increase in load factor represents an increase in performance). We considered whether the contribution of each parameter to the determination of the calculated first flight date seemed reasonable. For example, we would be suspicious of a technology equation in which the contribution of the carrier capability parameter dominated specific power and maneuverability combat parameters. We evaluated the magnitude and sign of the residuals (observed − calculated first flight date) to assess the ability of various parameter sets to describe the performance attributes of particular aircraft.

Statistical Quality

To evaluate the statistical quality of the technology expressions, we considered goodness of fit measures, significance measures, tests for independence and normality of the residuals, dispersion of the residuals, independence of the explanatory

variables, and stability of the technology expressions. We briefly introduce below the procedures we followed to evaluate statistical quality.[2]

To compare the accuracy or goodness of fit of the various technology equations, we examined the coefficient of determination (R^2), which indicates the proportion of variation in the dependent variable explained by the regression expressions, and the standard error of estimate (SEE), which indicates the absolute amount of unexplained variation.

We used the t-statistic to evaluate the significance of individual independent variables and the F-statistic for equations as a whole. We picked a decision rule such that the upper bound was less than 10 percent of incorrectly rejecting the null hypothesis that an individual equation coefficient was zero.[3]

To check for evidence of correlation among the residuals, we used the Durbin-Watson test on our sequential data set. We also plotted the observed residuals of key equations on normal probability paper to see if they approximated a normal distribution. The normality condition is necessary to make valid significance tests. Using scatterplots of the residuals, we checked for evidence of nonuniform dispersion about the regression surface.

We examined correlation matrices to check for high correlation among explanatory variables. We also made repeated random exclusions of 20 percent of the aircraft in the sample and reestimated the technology equations to test for the stability of the coefficients.

Not unexpectedly, a number of the technology equations do not entirely satisfy all the statistical tests to the degree desired. As we present the results, we will try to note the statistical qualities of the various expressions.

Predictive Properties

To see if the technology equations yielded plausible predictions for the time required to achieve postulated improvements in technology, we took known performance increments, such as that experienced in going from the F-4B to the F-15A, and evaluated how long it might take to achieve a comparable absolute increase in performance using the F-15A as a starting point. We then computed confidence intervals to characterize the level of uncertainty associated with these predictions.

TECHNOLOGY EQUATION RESULTS

Results of Origin Comparison

Because two of the equation forms were logarithmic in the dependent variable, first flight date, the selection of an appropriate origin from which we could measure time had considerable importance. The apparent rate of acceleration or deceleration in technology at a particular date for the logarithmic forms is sensitive to the origin selection. Several considerations enter into such a selection. First, so that the logarithm of the dependent variable always remained defined (having an argument greater than zero), we had to select an origin earlier than the earliest first flight

[2] Appendix D defines all the statistical measures referred to in this section.

[3] In a few cases, for comparison purposes, we present results that failed to meet this criterion.

date in the sample (the FH-1 flew in October 1946; the XP-80, a design antecedent of the F-94A, flew in January 1944). Second, so that the logarithmic equation forms were meaningfully different from the linear equation forms, we had to select an origin reasonably close to the earliest first flight date in the sample to capture the influence of the logarithm. At the same time, however, we recognized that as the origin approached the earliest first flight date, the argument of the logarithm also approached zero, which could introduce anomalous results (e.g., residual patterns evidence abnormalities, and standard errors of estimate grow).

With the realization that we could never say one particular origin selection was unequivocally correct, we parametrically considered several origin selections. Table 8 shows some of the statistical properties used to compare the equations having different origins. We also examined the significance of the individual equation coefficients and the distribution of residuals.[4] Although the equations using 1900 and 1920 origins had the smallest standard errors of estimate, by the other statistical evaluation measures, they generally had poorer statistical properties than the other equations. The residual scatterplots showed some evidence of a systematic bias in estimating the technology of contemporary designs and their equation coefficients were generally less significant than equations having 1930, 1940, or 1942 origins. The equation with an origin of 1945 also had generally poorer statistical properties than these latter three equations, including less significant coefficients and a less satisfactory distribution of residuals.

Table 8

STATISTICAL PROPERTIES OF THE LOG-LINEAR EQUATION FORM FOR SEVERAL TIME ORIGINS

Equation Origin[a] (January 1)	R^2[b]	SEE[c]	F Statistic	Durbin-Watson Statistic	Average of Absolute Values of Last Five Aircraft Residuals (months)
1900	.920	.042	43.5	1.54	35
1920	.929	.060	50.0	1.67	35
1930	.937	.077	56.8	1.80	35
1940	.945	.117	65.8	1.92	34
1942	.945	.137	64.8	1.86	34
1945	.930	.215	50.6	1.53	31

[a]Independent variables: specific power, sustained load factor, Breguet range, payload fraction, carrier capability; 25 observations.

[b]Coefficient of determination.

[c]Standard error of estimate.

Among the equations with origins of 1930, 1940, and 1942, we ultimately settled on the January 1, 1940, origin because it seemed to provide the best compromise in statistical properties. It yielded a more satisfactory residual distribution than the equation with a 1930 origin, particularly for contemporary aircraft, and had a

[4] Table D.1 gives more details of the statistical properties of the equations having different origins. Appendix D also has residual scatterplots for the corresponding equations.

smaller standard error of estimate than the equation with a 1942 origin. In all subsequent work we computed the dependent variable relative to January 1, 1940.

Results of Equation Form Comparison

The log-linear equation form unambiguously characterized the growth in U.S. fighter technology better than the other equation forms. Table 9 shows that it consistently exhibited better statistical properties than the other forms.[5] Examination of scatterplots of the residuals versus calculated first flight date also suggested freedom from abnormalities that might indicate violations in basic multiple regression assumptions about errors (see Appendix D for the scatterplots). Some of the other equation forms tested, particularly the linear-linear and linear-log forms, showed some evidence of abnormal residual patterns.

Table 9

STATISTICAL PROPERTIES OF FOUR EQUATION FORMS FOR 25 NEW DESIGNS THROUGH FLIGHT OF THE F-16A

Equation Form[a]	R^2	SEE[b]	F Statistic	Durbin-Watson Statistic	Average of Absolute Values of Last 5 Aircraft Residuals (months)
Log-linear	.945	.117[c]	65.8	1.92	34
Linear-linear	.895	34.7	32.5	1.31	35
Log-log	.885	.170[d]	29.2	1.15	63
Linear-log	.763	52.2	12.2	.71	64

[a]Independent variables: specific power, sustained load factor, Breguet range, payload fraction, carrier capability.

[b]Standard error of estimate expressed in logarithmic terms or in months, depending on the equation form.

[c]SEE of .117 around mean first flight date corresponds to +21.9, −19.4 months.

[d]SEE of .170 around mean first flight date corresponds to +32.6, −27.5 months.

Rejected Variables

Using the rationale introduced earlier in this section, we tested, evaluated, and rejected a number of variables.[6] Of the combat variables we evaluated, wing loading and combat ceiling did not satisfy significance tests. An examination of residuals suggested that the maximum speed variable was insensitive to the technology associated with packaging high performance in a small vehicle (e.g., the F-16), despite inclusion of the empty weight variable, which also failed significance tests.

[5] We show results for one set of independent variables, but we tested the attractiveness of the various equation forms using other variables as well. The log-linear form remained the most attractive for the other variable sets tested. Table D.1 of Appendix D summarizes the statistics of all the equation forms and variable sets tested.

We also considered using equations having exponents on the independent variables; however, plots of the equation residuals versus the independent variables showed no readily identifiable functional relationships that might profit from correction by exponents.

[6] Refer to Appendix D for details of the equations containing the rejected variables.

Expressions using maximum climb rate or maximum specific energy did not have as good explanatory power as expressions using specific power. The residual patterns also suggested a tendency to underestimate the technology of post-1960 aircraft. In the measure of maneuverability, the sustained load factor variable proved consistently more significant than the thrust-to-weight ratio variable.

Most of the range and payload variables satisfied both engineering and statistical criteria for inclusion; as a consequence, we will subsequently present technology equations using alternative sets of these variables. Only the useful load fraction failed to meet significance criteria, and separate measures of range and payload performance proved more descriptive than the product of the range and payload fraction.

The structural efficiency variable did not improve the statistical properties of the technology equations. The variable that distinguished airframe manufacturers did not meet the significance criteria. The dummy variables that identified whether an aircraft had variable geometry wings, a primary air-to-ground mission, or supersonic capability also failed to meet the significance criteria. Other variables adequately described speed performance and thus made the supersonic capability variable duplicative. Only three aircraft in our new design data base had variable geometry wings, and only three had a primary air-to-ground mission orientation. The paucity of aircraft in these categories made it difficult to identify any statistically discernible differences in these aircraft types. Moreover, other variables do measure certain distinguishing characteristics of these aircraft types, for example their range and payload performance.[7]

The design antecedent variable never met significance tests. The result was not so clear-cut for the design lag variable, which measured the time interval between first flight of the aircraft in our sample and flight of their earliest hardware antecedents. At times the variable was significant, at other times not. It had an unpredictable influence on the calculated first flight date, depending on the other independent variables with which it was used, sometimes yielding counterintuitive results for advanced aircraft having no hardware antecedent (e.g., the F-15A). Because it also did not demonstrably improve the goodness of fit of the equations, we chose not to use it.

Technology Equations

Table 10 shows three of the more desirable technology equations, each developed from the sample of 25 aircraft classified as new designs, and each having five independent variables. For illustrative purposes, Table 11 shows how to use Eq. (1) to obtain an aircraft's calculated first flight date. The parameters of the equations—which measure aspects of speed, maneuverability, range, and payload performance—reflect some, but certainly not all, important attributes that characterize the basic air vehicle technology of a jet fighter.

The equations have three variables in common: specific power, sustained load factor, and carrier capability. Given the considerable emphasis on speed performance during the evolution of jet fighter aircraft, it is not surprising that specific power appears in each equation. The carrier capability variable, by its definition (1 = no capability, 0 = capability) and by the negative sign of its coefficient,

[7] Section IV considers the issue of air-to-ground fighters in more detail.

Table 10

U.S. Fighter Aircraft Technology Equations

$$(1)\ \ln(t) = \underset{(.001)}{3.878} + \underset{(.001)}{.065}\left|\frac{\text{Thrust}\cdot\text{Vmax}}{100\,W_{cbt}}\right| + \underset{(.00001)}{.406}\left[\frac{\text{Breguet Range}}{1000}\right] + \underset{(.001)}{1.409}\left[\frac{\text{Sustained Load Factor}}{10}\right] + \underset{(.020)}{.939}\left|\text{Payload Fraction}\right| - \underset{(.100)}{.093}\left|\text{Carrier Capability}\right|$$

$$(2)\ \ln(t) = \underset{(.0001)}{3.643} + \underset{(.0001)}{.072}\left|\frac{\text{Thrust}\cdot\text{Vmax}}{100\,W_{cbt}}\right| + \underset{(.010)}{1.257}\left[\frac{\text{Breguet Range Factor}}{10{,}000}\right] + \underset{(.005)}{1.184}\left[\frac{\text{Sustained Load Factor}}{10}\right] + \underset{(.005)}{.876}\left[\text{Internal Fuel Fraction}\right] - \underset{(.100)}{.105}\left|\text{Carrier Capability}\right|$$

$$(3)\ \ln(t) = \underset{(.005)}{3.530} + \underset{(.005)}{.059}\left|\frac{\text{Thrust}\cdot\text{Vmax}}{100\,W_{cbt}}\right| + \underset{(.001)}{1.768}\left[\frac{\text{Breguet Range Factor}}{10{,}000}\right] + \underset{(.010)}{1.186}\left[\frac{\text{Sustained Load Factor}}{10}\right] + \underset{(.050)}{.526}\left[\text{Total Fuel Fraction}\right] - \underset{(.020)}{.168}\left|\text{Carrier Capability}\right|$$

Equation	R^2	SEE	F
(1)	.945	.117	65.8
(2)	.938	.125	57.2
(3)	.922	.140	45.2

NOTES: t=calculated first flight date measured in months since January 1, 1940.
Each equation is based on 25 observations and has 5 and 19 degrees of freedom.
Upper bound for risk of incorrectly rejecting the null hypothesis that a coefficient is really zero is shown in parentheses below the coefficients.
Thrust measured in pounds, Vmax in knots, combat weight in pounds.
Carrier capability variable: 1 denotes no capability, 0 denotes capability.
SEE of .117 around mean first flight date in sample corresponds to + 21.9, - 19.4 months.
Refer to Appendixes A and B for full variable definitions.

Table 11

COMPUTATION OF CALCULATED FIRST FLIGHT DATE FOR THE F-106A

Parameter	Coefficient[a]		Parameter Computation[b]		Product
Constant	(3.878)	•	(1)	=	3.878
Specific power	(.065)	•	$\left(\frac{18450 \cdot 1153}{100 \cdot 29940}\right)^c$	=	.462
Breguet range	(.406)	•	$\left(\frac{1349}{1000}\right)$	=	.548
Sustained load factor	(1.409)	•	$\left(\frac{3.20}{10}\right)$	=	.451
Payload fraction	(.939)	•	(.089)	=	.084
Carrier capability	(-.093)	•	(1)	=	-.093
			ln (calculated first flight date)	=	5.330
			calculated first flight date	=	206 months since Jan. 1, 1940 (March 1957)
			actual first flight date	=	204 months since Jan, 1, 1940 (Dec. 1956)
			residual = actual - calculated flight date	=	204 - 206 = -2 months

[a]Coefficients from technology Eq. (1).
[b]Parameter values from Table A.1.
[c]Thrust in pounds, velocity in knots, weight in pounds, conversion factor absorbed in coefficient.

suggests the greater difficulty of designing an aircraft to operate from the deck of a carrier, or conversely, that a land-based aircraft of equivalent performance might fly somewhat sooner.[8]

The remaining variables describe, in alternative ways, the range and payload performance of jet fighters. The parameters used in the first equation, payload fraction and Breguet range, perhaps measure military usefulness with respect to range and payload better than the variables used in the last two equations because range and payload fraction directly measure how far an airplane can fly and how much it can carry. The latter two equations rely on the disaggregated components of the Breguet range equation, range factor, and either internal fuel fraction or total fuel fraction to describe range and payload performance.

The first equation measures internal fuel plus external payload carriage, the third measures internal and external fuel carriage, but the second measures only internal fuel carrying capability. Thus, only the first and third equations measure

[8] Alternatively, this dummy variable could also be correcting for differences in Air Force and Navy development practices that could influence the flight date of an aircraft. Although this is only a hypothesis, we do know that the incorporation of a carrier capability does impose a weight penalty (see Sec. II).

loads carried externally. Of course, the ability to carry a variety of external loads has contributed to the versatility of modern multi-mission fighter aircraft.

These technology equations seemingly exhibit excellent explanatory powers, but they do have weaknesses. First, the equations do not seem suitable for making subtle distinctions between similar fighter designs because of limitations in the descriptive power of the variables and the sizable standard errors of estimate. Our examination of confidence intervals in Sec. V will reinforce this notion by quantifying the large uncertainty associated with making projections using the equations. Second, the small sample size (25) relative to the number of independent variables (5) contributes to some instability in the equations. A stability test (documented in Appendix D) showed that randomly excluding five aircraft from the sample did not appreciably change the coefficient of determination, the standard error of estimate, or the signs of the coefficients, but it did in some instances considerably change the values of some coefficients (changes as great as 67 percent). Third, two of the variables in the equations, specific power and sustained load factor, are highly correlated (.74 correlation coefficient), which, in combination with the small sample size, could contribute to coefficient instability.[9]

Further work might permit the identification and development of some parameters having more descriptive power than the present set, but we expect that the many analytically unquantifiable factors that influence the flight date of an aircraft (Congressional or service funding decisions, for instance) will make it difficult to improve the precision of the equations. There will always be a problem of a small sample size, although we can evaluate the technology expressions using similar data samples, such as Soviet aircraft data, to see whether the results still make intuitive sense.[10]

In an attempt to alleviate the correlation problem, we tried and rejected some alternative variable formulations describing maneuverability; none was as satisfactory as sustained load factor, and each also exhibited high correlation with specific power. We redetermined Eq. (1) omitting sustained load factor (see Eq. (4) in Table 12). The equation with sustained load factor was of much better statistical quality and gave more intuitively satisfying residuals for contemporary aircraft than did the equation without it. Hence, we obtained a better estimating relationship by incorporating a historically correlated combination. If the nature of the relationship between specific power and sustained load factor changes in the future, then the estimating relationship may become less useful for predictive purposes.

Finally, we recognize that analysts differ in their preferences about rejection criteria for the coefficients of independent variables. More specifically, some might prefer excluding the carrier capability variable on statistical grounds because of the 10 percent probability of incorrectly rejecting the null hypothesis for its coefficient in Eqs. (1) and (2). We justify inclusion of the variable because it measures a capability the other variables do not measure and consequently makes an intuitively satisfying adjustment in the calculated first flight dates of the Navy aircraft in the sample. Furthermore, its observed influence is consistent with quantifiable and not speculative evidence.[11] Nonetheless, in Table 12 (Eq. (5)), we have redeter-

[9] See Appendix D for a complete correlation matrix.

[10] See Sec. V.

[11] The variable recognizes the carrier capability by increasing the calculated first flight date of the Navy aircraft in the sample. By not accounting for the carrier capability, Eq. (5) suggests a lower level of technology (i.e., smaller calculated first flight dates) for the carrier-capable aircraft.

Table 12

SOME ALTERNATIVE TECHNOLOGY EQUATIONS

		R^2	SEE	F
Equation (1) without sustained load factor variable				
(4)	$\ln(t) = \underset{(.000001)}{4.126 + .105} \left\lvert \frac{\text{Thrust} \cdot \text{Vmax}}{100\ W_{cbt}} \right\rvert \underset{(.001)}{+ .368} \left[\frac{\text{Breguet Range}}{1000} \right] \underset{(.500)}{+ .552} \left\lvert \text{Payload Fraction} \right\rvert \underset{(.500)}{- .057} \left\lvert \text{Carrier Capability} \right\rvert$	.892	.161	41.2
Equation (1) without carrier capability variable				
(5)	$\ln(t) = \underset{(.001)}{3.871 + .062} \left\lvert \frac{\text{Thrust} \cdot \text{Vmax}}{100\ W_{cbt}} \right\rvert \underset{(.0001)}{+ .406} \left[\frac{\text{Breguet Range}}{1000} \right] \underset{(.001)}{+ 1.32} \left[\frac{\text{Sustained Load Factor}}{10} \right] \underset{(.05)}{+ .923} \left\lvert \text{Payload Fraction} \right\rvert$	.936	.124	73.2
Equation (1) without both variables				
(6)	$\ln(t) = \underset{(.000001)}{4.111 + .101} \left\lvert \frac{\text{Thrust} \cdot \text{Vmax}}{100\ W_{cbt}} \right\rvert \underset{(.001)}{+ .370} \left[\frac{\text{Breguet Range}}{1000} \right] \underset{(0.5)}{+ .558} \left\lvert \text{Payload Fraction} \right\rvert$	.888	.160	55.5

NOTES: Each equation is based on 25 observations, Eqs. (4) and (5) have 4 and 20 degrees of freedom.
Equation (6) has 3 and 21 degrees of freedom.
Upper bound for incorrectly rejecting the null hypothesis that a coefficient is really zero is shown in parentheses below that coefficient.
$\hat{t}$ = calculated first flight date measured in months since January 1, 1940.

mined an equation excluding the carrier capability variable, as well as an additional equation that also excludes sustained load factor (Eq. (6)). Some analysts may prefer Eq. (5) to Eq. (1).

Figure 4 is a graphical representation of Eq. (1).[12] The vertical axis measures the first flight date calculated by inserting aircraft performance parameters in the technology equation and the horizontal axis measures the actual first flight date for each aircraft. The distribution of the 25 data points about the 45° line provides one measure of how well the equation fits the data sample. Points plotted above the 45° line represent aircraft that flew earlier than the date predicted by the equation, and the converse holds for points plotted below the line. The magnitude and sign of the

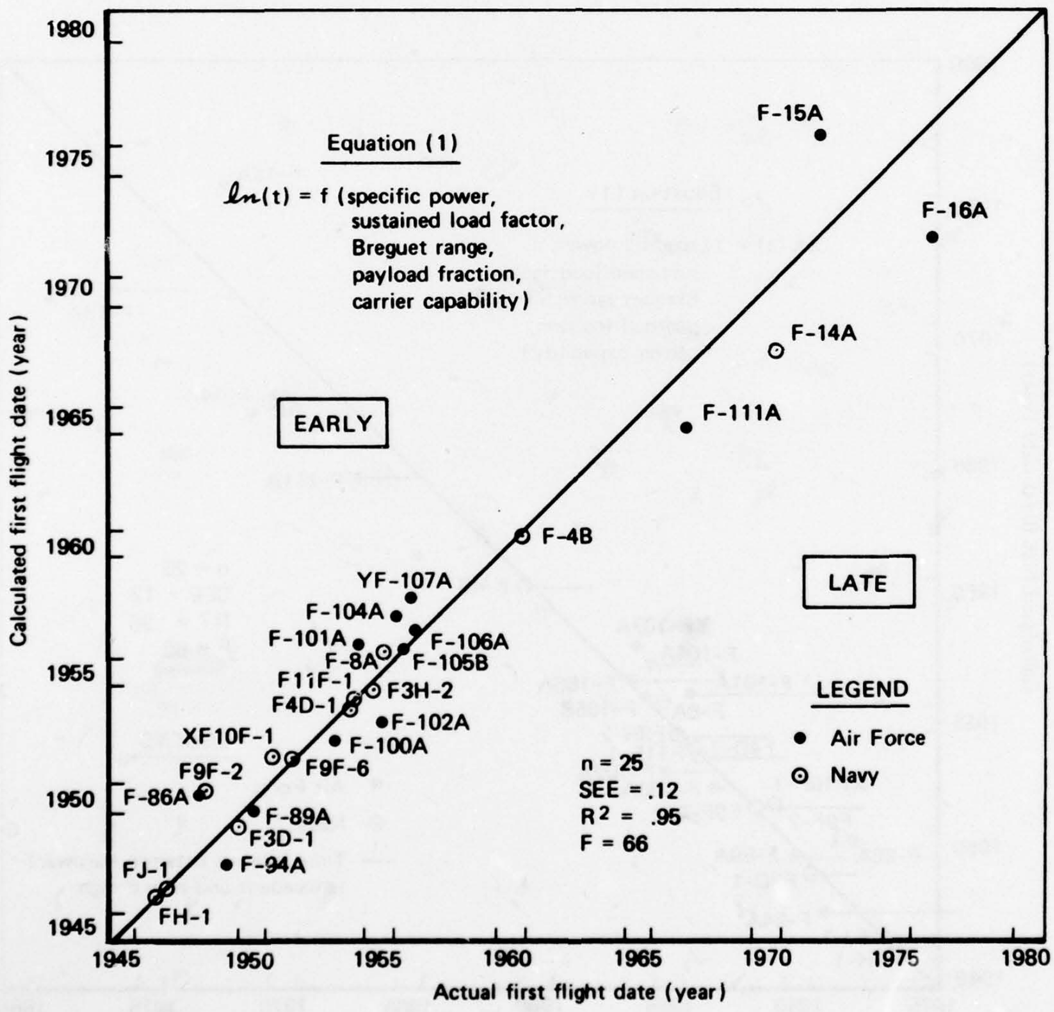

Fig. 4—Multivariable technology trend for U.S. aircraft

[12] Figures D.7 and D.8 in Appendix D show graphical representations of Eqs. (2) and (3).

residual of the technology equation determine where a particular aircraft point falls relative to the 45° trend line, with the residual representing all the unquantifiable factors that influence when the first flight of an aircraft occurs, including technological factors not covered by the independent variable parameter set, scheduling decisions, Congressional and service funding decisions, development philosophy, etc. Accordingly, one should interpret the results from the equation only as a gross indication of average technological trends in fighter aircraft development, remembering that other factors can also influence the time at which a particular level of technology becomes available.

We have reproduced the graphical representation of technology Eq. (1) in Fig. 5 to illustrate our previous observation that the absence or presence of a design antecedent does not offer a consistent explanation for the position of particular

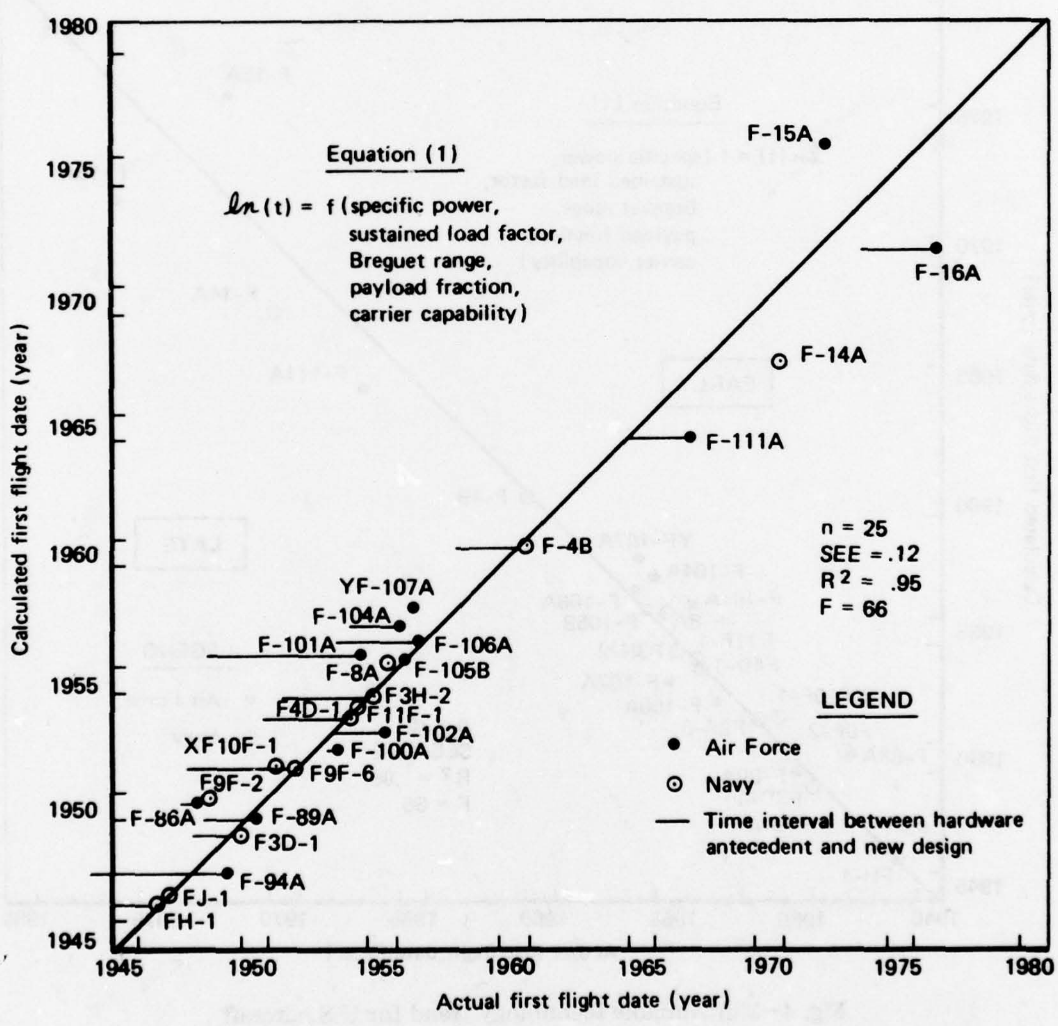

Fig. 5—Multivariable technology trend showing flight dates for hardware antecedents

aircraft relative to the 45° line. Programs using very extensive and deliberate experimental or prototype testing, or at least having a long design lineage, might account for some aircraft appearing below the 45° line in Fig. 5. Although some examples tend to support this contention (e.g., we can trace the design lineage of the F-94A back to the XP-80, which flew many years earlier), there is no consistent pattern.

IV. MEASURING TECHNOLOGICAL CHANGE IN DERIVATIVE DESIGNS AND OTHER AIRCRAFT TYPES

Limiting this analysis to aircraft the military services have classified as fighters and separating aircraft into new and derivative design categories involved making some subjective decisions. We now have an approach that allows us to compare technological change in new aircraft with those classified as derivatives. Moreover, although it seems unrealistic ever to expect complete agreement on the appropriate constitution for the data base, at least we have a reference point for comparing the effect of excluding or including certain aircraft.

TECHNOLOGY GROWTH THROUGH DERIVATIVES

The Air Force and the Navy have for many years relied on manufacturers to exploit the characteristics of existing aircraft models to develop derivative aircraft that can satisfy new operational needs. Presumably, at some point in the design life of each aircraft, the changes in design for the incremental performance improvement either become prohibitively costly or physically impossible, and the engineer must design a completely new aircraft to meet performance requirements. As the costs of developing new fighter aircraft weapon systems have grown, the introduction of derivative aircraft has become a particularly important means for incrementally introducing new technology. But can an engineer working within the constraints of an existing design improve air vehicle technology at a rate comparable to that achieved through the introduction of completely new aircraft?

The simple comparison shown in Table 13 of the air vehicle performance of 12 derivative aircraft with their initial operational predecessors[1] suggests that in a majority of cases, designers have improved performance, at least when measured by the parameter set of technology Eq. (1). Although this finding may seem obvious, the primary impetus for developing a derivative aircraft may not always be to improve basic air vehicle performance. For example, the services sometimes emphasize enhancements to armament or electronics systems.

To compare the rate of advance in air vehicle technology for new and derivative aircraft, we substituted the performance characteristics of the derivative aircraft into Eq. (1) and evaluated the technological advance achieved by the derivative after flight of the original aircraft. Figure 6 illustrates the results, with the solid dots representing the level of technology of the original aircraft and the open dots representing the level of technology of the derivatives. The slope of the connecting lines represents the rate of technological advance achieved in going from the original aircraft to the derivative. Two-thirds of the derivative aircraft have growth slopes less than 45°, suggesting that for these aircraft, at least, technology advanced at a somewhat slower rate than the trend for new designs.[2]

[1] See Table 5 for a tabulation of the 12 pairs of new and derivative fighters.

[2] The new designs are generally evenly distributed around the 45° line (see Fig. 4).
The striking difference shown in Fig. 6 between the calculated first flight dates of the F-4B and F-4C deserves some comment. Because of changes in landing gear design and other systems, the F-4C could

Table 13

QUALITATIVE EXPRESSION OF DERIVATIVE AIRCRAFT PERFORMANCE CHANGE

Derivative Aircraft	Qualitative Change in Performance Relative to Operational Predecessor[a]				
	Specific Power	Breguet Range	Sustained Load Factor	Payload Fraction	Carrier Capability[b]
F2H-1	+	+	+	-	
F2H-3	+	+	+	+	
F-86D	+	-	+	-	
YF-93A	-	+	-	-	
F-86H	+	+	+	+	
FJ-3	+	+	+	+	+
FJ-4	+	+	-	-	+
F-89C	+	-	-	+	
F-94C	+	-	+	+	
F5D-1	no change	+	-	-	
F-104G	-	-	+	-	
F-4C	-	-	+	+	-
Improvement: Fraction of total	8/12	7/12	8/12	6/12	N/A

[a] + (-), better (poorer) performance. See Table 5 for the listing of new and derivative aircraft.

[b] Carrier capability + (-), added (deleted).

One might hypothesize that to achieve a rate of technological advance equivalent to that for new designs requires the incorporation of a new engine[3] in the derivative aircraft. Three of the four derivative aircraft having growth slopes greater than 45° used new engines; but four of the remaining eight aircraft having growth slopes less than 45° also incorporated new engines.

When we compared the average slope for the seven derivative aircraft that incorporated new engines with the slope for the five aircraft that did not, we obtained a less ambiguous result. We found that the minimum slope among the seven aircraft was 31°, the average slope was 43°, and the average thrust increase for the new engines was a robust 70 percent. The five aircraft that did not incorporate new engines had an average technological growth curve slope of 0° and an average thrust increase of only 12 percent. Consequently, for our limited sample of aircraft, the incorporation of new engines did substantially influence the rate of technological advance achieved.

The aircraft that incorporated new engines exhibited a technological growth rate almost comparable to that for new designs. These seven derivative aircraft, all of which had flown by 1955, benefited from the rapid advance in jet engine technol-

not operate from aircraft carriers, although it obviously retained many of the inherent design features the F-4B incorporated for carrier operations. The technology equation recognizes only the deletion of the carrier capability, which alone accounts for 58 percent of the difference in calculated flight dates. Changes to make the aircraft suitable for TAC use also caused slight degradation in some areas of air vehicle performance as measured by the four performance parameters in technology Eq. (1). [11] Those performance changes explain the rest of the difference in F-4B and F-4C calculated flight dates.

[3] By new, we do not mean a variant of the engine included in the original aircraft.

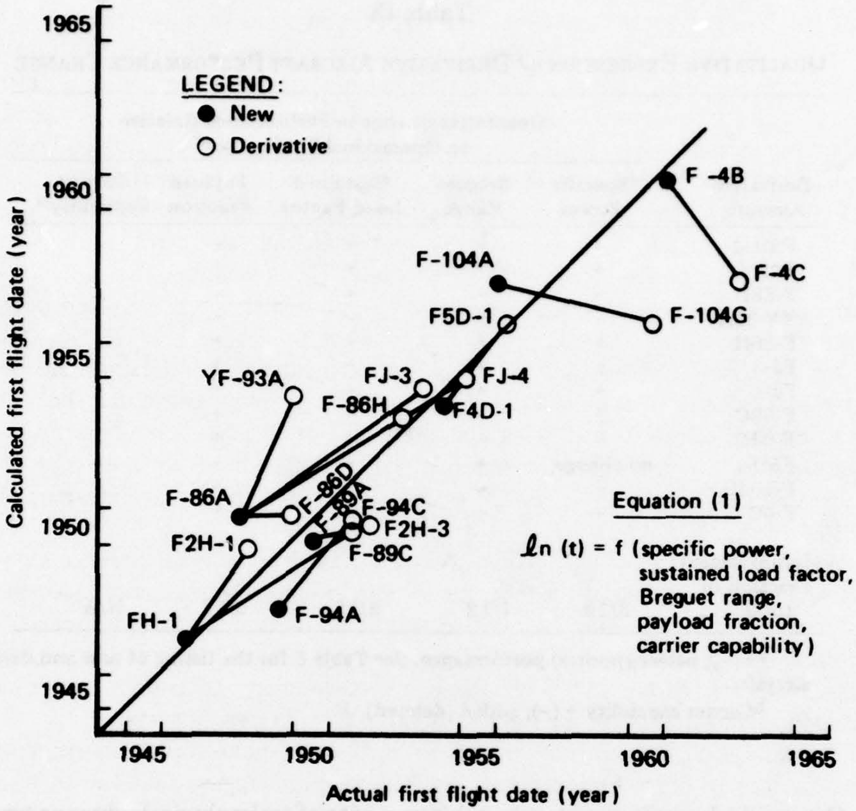

Fig. 6—Technology growth through derivatives

ogy as it matured from its infancy. Subsequent experience suggests that current and future designers of derivative aircraft will rarely have engine substitution options comparable to those available during the 1940s and early 1950s. As a result, when working within the constraints of an existing design, designers will probably find it extremely difficult to match the rate of technological advance exhibited by new designs.

SENSITIVITY TO INCLUSION AND EXCLUSION OF CERTAIN AIRCRAFT

Including Derivative Fighters

Partitioning the data sample into new and derivative categories involved making some subjective judgments, which raises the inevitable question about the effect of failing to include certain aircraft. To address this issue, we interpreted the results obtained in measuring technological growth through derivatives, and we performed several tests. The risk of understating the rate of advance by excluding derivative aircraft seems small, because about two-thirds of the derivative aircraft

in the sample had a rate of advance less than the average for new designs. At best, the derivative aircraft incorporating new engines exhibited an average technological growth rate about comparable to that for new designs. Moreover, a desire to make major improvements in air vehicle performance has not always been the motivating factor for developing derivative aircraft. Hence, the inclusion of derivative aircraft is probably not necessary to properly characterize the technological tradeoff frontier, because derivative designs seldom define that frontier.

We created a dummy variable that identified the derivative aircraft in the sample. The results of this test were inconclusive. The variable was significant only at the 0.2 level, suggesting a somewhat ambiguous distinction between new and derivative aircraft.

We identified five derivative aircraft that incorporated considerable design changes, added them to the sample of 25 new designs, and reestimated the technology equations.[4] Table 14 indicates that the inclusion of these aircraft had a mixed and generally modest influence on both cruise and combat variable coefficients. Figure 7 suggests that their inclusion did not change the basic character of the results.[5]

We also estimated an equation adding all 14 derivative aircraft to the data sample. Table 14 demonstrates that this sample induced a more pronounced change in the equation coefficients than did the addition of five derivative aircraft.[6] The equation results, shown in Fig. 8, suggest a less ambitious technological trend, which rates the F-15A and F-16A higher in technology than does the equation developed from the more homogeneous sample of 25 new designs.

The analysis of derivative aircraft permits us to make some general observations but not to draw firm conclusions. The results suggest that the technology equations developed from the 25 aircraft sample do not suffer appreciably from the exclusion of the five derivative aircraft. The five aircraft do contribute to enlarging the data sample, but the technology trend for the 1950 time period is already well defined by other new designs in the sample.

The heterogeneous mix of 14 derivative aircraft raises questions about the validity of any trend derived from a sample that incorporates all these aircraft. The idea of using only new designs has considerable appeal. We have sought to develop an approach for estimating technological trends in the development of new aircraft, which is usually a far more difficult task than estimating technological growth possibilities for well-known existing designs. Hence, the emphasis on new designs seems appropriate.

Excluding Air-to-Ground Fighters

Three of the 25 aircraft in the new design sample had a strong air-to-ground mission orientation, the F-105B, the YF-107A, and particularly the F-111A. Concern that these three aircraft might distort the overall trend for the other aircraft that had more of an air-to-air mission orientation led us to perform several tests.

[4] We added the YF-93A, F-86D(F-95), F-84F(F-96), F-94C(F-97), and the F-86H. Reference [12] describes the design changes these aircraft incorporated.

[5] The results shown in Fig. 7 are generally representative of the magnitude of changes that occurred when using variables from Eqs. (2) and (3).

[6] The carrier capability variable loses some significance, which is not particularly surprising, because the derivative aircraft sample contains examples of aircraft developed by one service but modified for use by another (e.g., F-4C, FJ-3, FJ-4).

Table 14

INCLUDING DERIVATIVE AIRCRAFT: COMPARISON WITH EQ. (1) COEFFICIENTS

Parameter[a]	Value of Coefficient: 25 Aircraft Sample Eq. (1)	30 Aircraft Sample[b]	39 Aircraft Sample (all new and derivative aircraft)
Constant	3.88	3.89	3.90
Specific power	.065	.070	.070
	(.001)[c]	(.00001)	(.00001)
Sustained load factor	1.41	1.35	1.19
	(.001)	(.001)	(.002)
Breguet range	.406	.360	.350
	(.00001)	(.00001)	(.0001)
Payload fraction	.939	1.13	1.42
	(.02)	(.002)	(.001)
Carrier capability	-.093	-.116	-.062
	(.1)	(.05)	(.5)
R^2	.95	.93	.87
SEE	.117	.122	.157
F	65.8	63.7	42.5

[a]Appendix G presents comparable information for the other two major parameter sets.

[b]25 "New" designs plus the YF-93A, F-86D, F-84F, F-94C, and the F-86H.

[c]Upper bound for probability of incorrectly rejecting the null hypothesis.

We tested a dummy variable that identified each aircraft's mission orientation, but it was not even marginally significant. We believe that the existing variables in the technology equations, including cruise variables, adequately quantify the design tradeoffs for the three aircraft.

We excluded the three air-to-ground fighters from the data base, separately and collectively, and reestimated the technology equations. Exclusion of the F-111A produced the greatest change in equation coefficients. Expressions estimated without the air-to-ground fighters emphasized combat performance more and cruise performance less (see Table 15), but the changes did not have a major influence on the calculated first flight dates of the remaining aircraft in the sample. Figure 9 shows that most of the data points estimated from equations using 25 and 22 aircraft samples nearly coincided.[7] We concluded, therefore, that there was no particular advantage in excluding the F-105B, the YF-107A, or the F-111A from the data sample.

[7] Appendix G shows the changes in coefficients for the variable sets used in Eqs. (2) and (3). Results using the Eq. (3) variable set, depicted in Fig. G.1, showed the greatest changes.

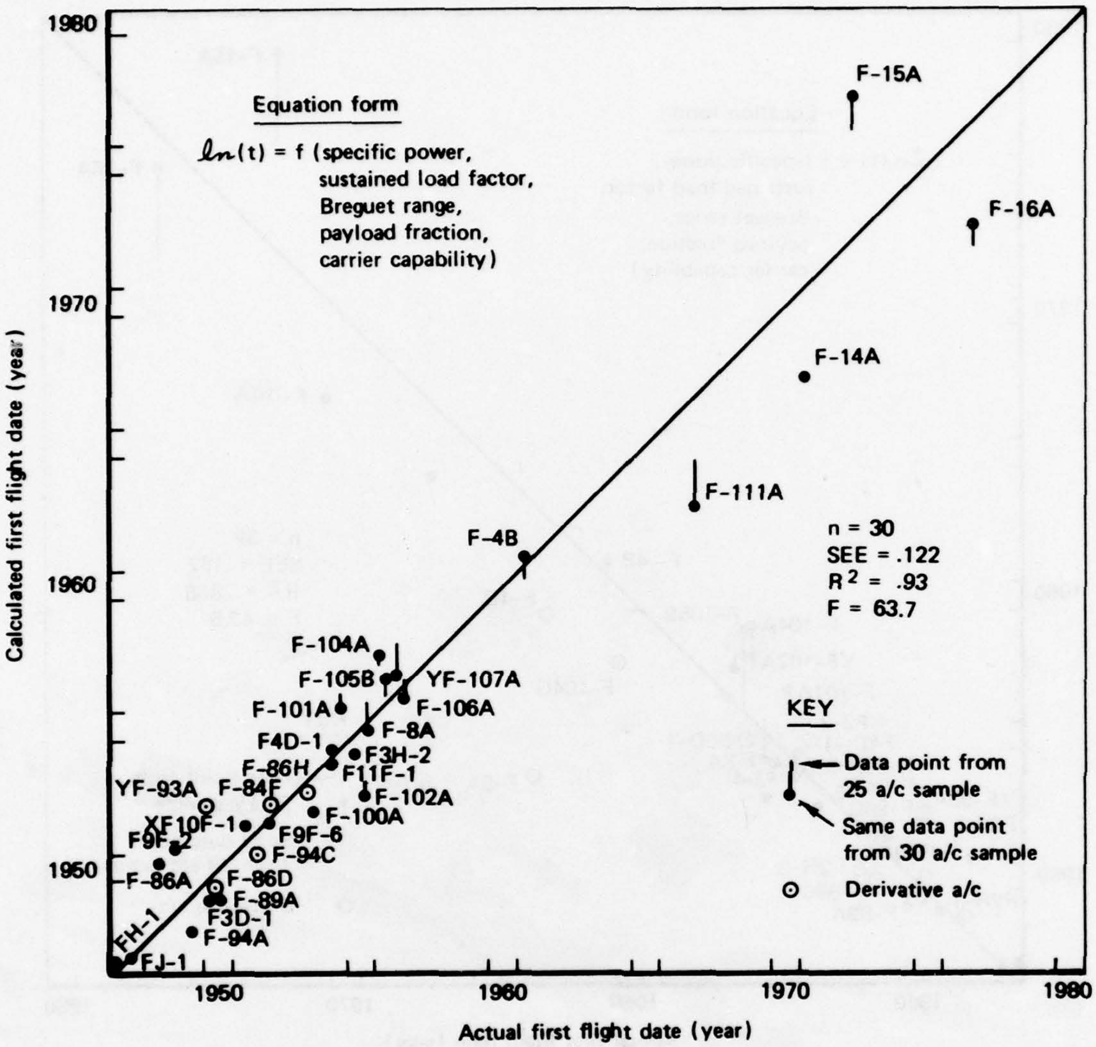

Fig. 7—Effect of including five derivative aircraft

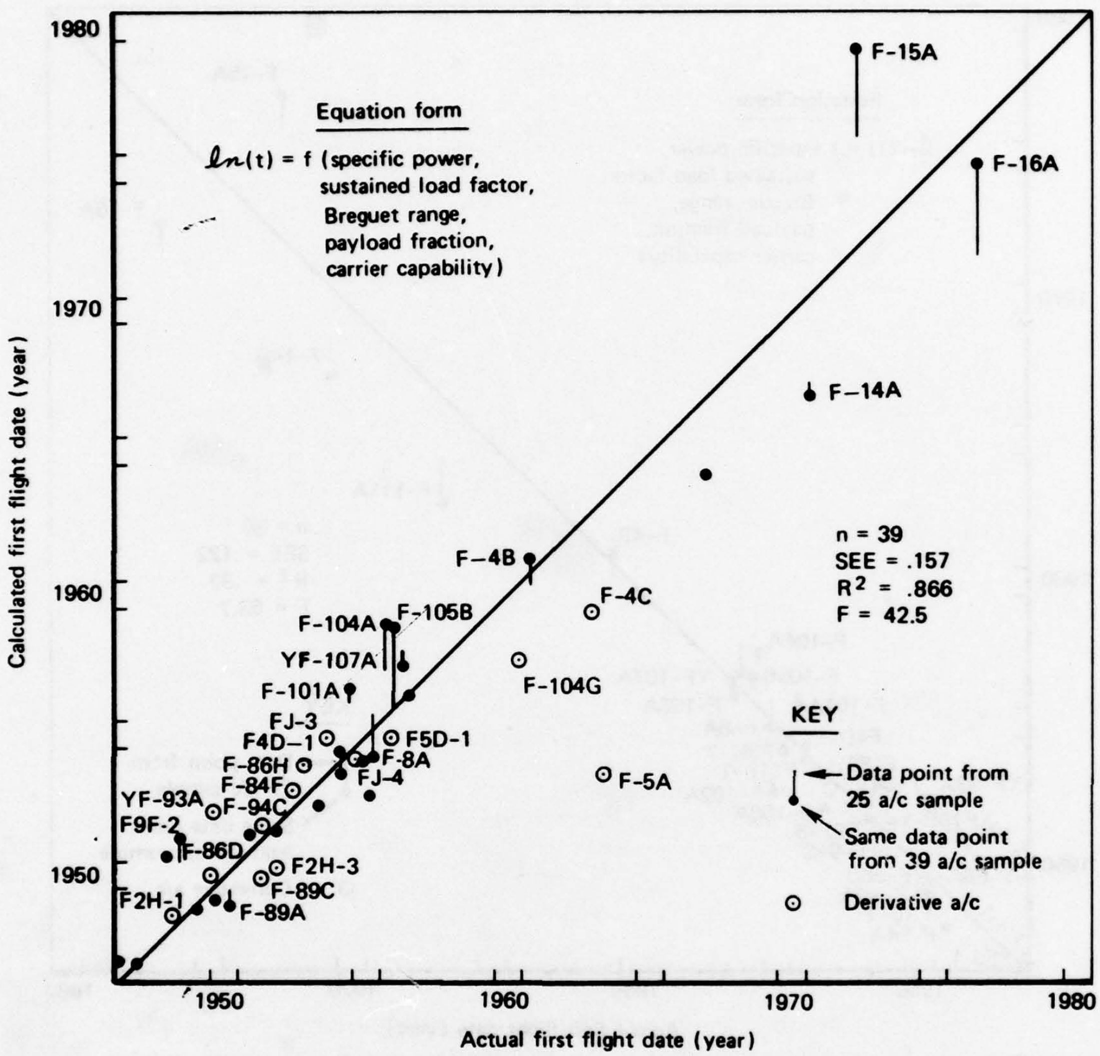

Fig. 8—Effect of including all 14 derivative aircraft

Table 15

RESULTS FROM EXCLUDING AIRCRAFT THAT EMPHASIZE AIR-TO-GROUND MISSION PERFORMANCE: COMPARISON WITH EQ. (1) COEFFICIENTS

	Value of Coefficient		
Parameter[a]	22 Aircraft Sample[b]	24 Aircraft Sample (excludes F-111A)	25 Aircraft Sample Eq. (1)
Constant	3.99	4.00	3.88
Specific power	.068 (.001)[c]	.069 (.0001)	.065 (.001)
Sustained load factor	1.51 (.001)	1.53 (.001)	1.41 (.001)
Breguet range	.321 (.02)	.304 (.01)	.406 (.00001)
Payload fraction	.673 (.2)	.679 (.2)	.939 (.02)
Carrier capability	-.110 (.1)	-.116 (.05)	-.093 (.1)
R^2	.95	.95	.95
SEE	.121	.115	.117
F	55.5	62.4	65.8

[a]Appendix G presents comparable information for the other two major parameter sets.

[b]Excludes F-105B, YF-107A, and the F-111A.

[c]Upper bound for probability of incorrectly rejecting the null hypothesis.

EVALUATING OTHER AIRCRAFT TYPES

Aside from questions about including or excluding certain air-to-ground or derivative fighters from the sample, we also considered the applicability of the fighter technology equations to the evaluation of other aircraft types. To do so, we identified some of the differences in mission requirements among fighters, bombers, and attack aircraft that influence their performance, inserted the characteristics of some bomber and attack aircraft in the fighter technology equations, and evaluated the results. Subject to some qualifications, the results suggested that the fighter technology equations cannot generally be extended to the analysis of other aircraft types.

Mission requirements for bombers and attack aircraft have usually placed more emphasis on range and payload performance than have fighter requirements. Maneuverability requirements have usually been less stringent for bombers. Typically, bombers have had design limit load factors of about 2 g (the load factor the pilot must not exceed in flight), and fighter aircraft have usually had a 7.3 g limit. This higher limit is one of the key distinctions between bombers and fighters, for it translates directly into a need for a structure capable of withstanding greater loads and more propulsion to compensate for the extra weight.

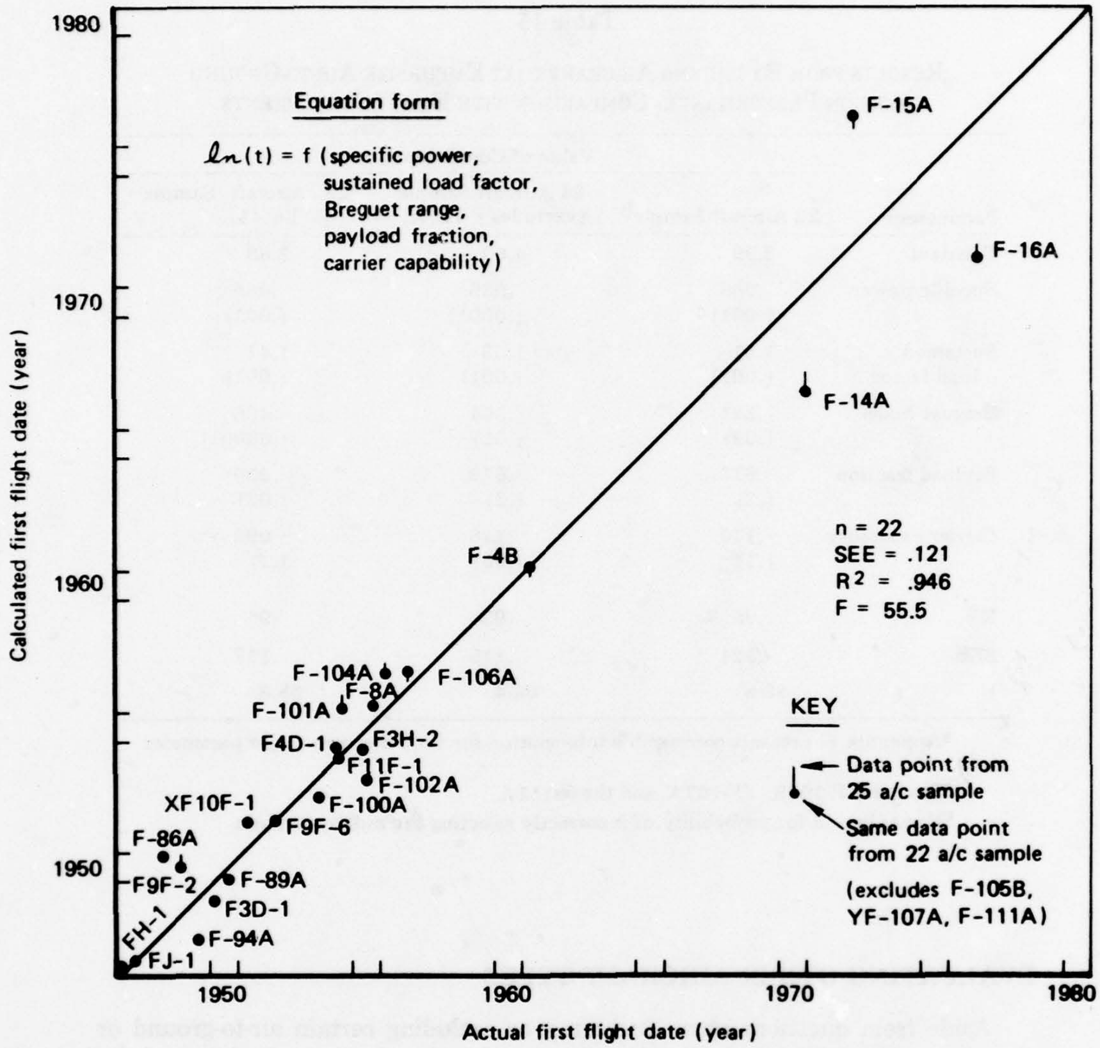

Fig. 9—Effect of excluding fighters having air-to-ground mission emphasis

Design limit load factors for attack aircraft have not differed appreciably from those for fighters, because attack aircraft must withstand the high loads imposed when they are pulling out from dive bombing runs. Although fighters and attack aircraft do share comparable limit load factors, designers of attack aircraft have often consciously not sought maximum propulsive performance, recognizing that the attack mission did not demand it; hence, the F-111A and the A-7A share the same basic engine, but only the F-111A incorporates an afterburner.

When we compared the performance of bomber, attack, and fighter aircraft, these differences showed up quite clearly. Table 16 suggests that bombers and attack aircraft have exhibited superior performance in range and fuel carriage, but they have generally lagged behind fighters in specific power and sustained maneuverability.

If the performance parameters shown on the left in Table 16 represented the major parameters that designers manipulated to satisfy attack and bomber mission requirements, and if the parameter space represented in the data base was broad enough to quantify the range of tradeoffs made to satisfy attack and bomber mission requirements, then we might confidently use the fighter technology equations to compare the technology of fighters and other aircraft types. After inserting the characteristics of two bombers and three attack aircraft into technology Eqs. (1), (2), and (3) and evaluating the results, we suspect that neither of the above conditions is satisfied.

Both the heavy subsonic B-52A and the lighter supersonic (Mach 2) B-58A flew much earlier than the trend suggested (see Table 17). We believe this occurs because the Breguet range, range factor, and fuel fractions for the two aircraft lie far outside the parameter space defined by the technology equations (e.g., the bombers have ranges two to three times greater than even the F-111A and total fuel fractions 50 percent greater than the best fighter fuel fraction). Although we would have to evaluate more bombers to draw definitive conclusions, we suspect that the design tradeoff regions used by the bomber designer do not overlap enough with

Table 16

COMPARISON OF ATTACK/BOMBER AIRCRAFT AND FIGHTER AIRCRAFT PERFORMANCE

	Aircraft Model									
Performance Category	B-52A	B-58A	A-3A	A-4A	A-5A	A-6A	A-7A	A-7D	A-10A	F-111A[a]
Specific power	–[b]	–	–	–	–	–	–	–	–	–
Sustained load factor	–	–	?[d]	?	?	–	–	–	–	–
Breguet range	+[c]	+	?	?	?	–	+	–	–	+
Breguet range factor	+	+	?	?	?	–	+	–	–	+
Payload fraction	–	–	–	–	–	–	–	–	–	–
Fuel fraction (int.)	+	+	+	+	+	+	+	–	–	+
Total fuel fraction	+	+	+	+	–	+	+	–	–	+

[a]Included for reference purposes only.

[b]– means at least *one previous new design fighter* in sample exhibited better performance.

[c]+ means performance in particular category better than *any previous new design fighter* in sample.

[d]? means performance information not readily available.

Table 17

TESTING OTHER AIRCRAFT TYPES IN THE TECHNOLOGY EQUATIONS

	Residual (observed - calculated flight date in months)[a]		
Aircraft	Eq. (1)	Eq. (2)	Eq. (3)
B-52A	-1767	-378	-282
B-58A[b]	-548,-792	-28,-89	-78,-153
A-6A	42	46	32
A-7A	52	60	42
A-7D	138	141	115

[a]- indicates aircraft flew earlier than equation predicted. + indicates the reverse.

[b]Two values shown, assuming the B-58A can sustain 1 g or 3 gs (M = .8, altitude = 25 kft). A lack of complete performance information prevented an exact computation.

those used by the fighter designer to reliably measure the level of technology of bombers using the fighter technology equations.

Results are far more ambiguous for the subsonic attack aircraft cases. Both the A-6A and the A-7A[a] flew later than suggested by the fighter equations, but their departure from the trend is not much greater than that of some of the fighters in the sample (e.g., the F-16A and F-111A). Although the two attack aircraft generally have better range and fuel fraction characteristics than predecessor fighters, they did not exhibit particularly impressive combat performance, perhaps because it was not needed to satisfy their mission. We have only fragmentary performance information for other attack aircraft, but we suspect that additional evaluation would yield results similar to those obtained for the A-6A and A-7A because of the importance of combat performance in the equations.

We also suspect that the technology equation parameter set, tailored to measure important fighter attributes, probably ignores some important attributes of attack aircraft, such as loiter performance, low altitude maneuverability, and vulnerable area as a fraction of total area. Although the present formulation of the equations does not seem suitable for evaluating the level of technology of attack aircraft or bombers, attack aircraft clearly have much more in common with fighters than do bomber aircraft.

[a] We include the A-7D, unambiguously a derivative design, for reference purposes only.

V. MEASURING TECHNOLOGICAL TRENDS

To better understand the strengths and weaknesses of the approach, we used it to chart improvement in the various performance categories through time, to identify possible changes in the rate of technological advance in the past, to infer trends in technological change for the future, and to compare trends in U.S. and Soviet jet fighter technology.

MISSION TRADEOFFS AND PERFORMANCE IMPROVEMENT THROUGH TIME

One of the more desirable features of our technology trending approach is that in a gross sense it allows us to distinguish between performance improvements made possible by mission tradeoffs and those brought about by technological advances. We can do so by examining in Fig. 10 the contribution of each term of the technology equation to the calculated first flight date of each aircraft. We see a generally increasing trend in specific power through the years, although designers have at times sacrificed specific power to satisfy cruise requirements (e.g., the F-111A).[1]

Until the 1970s, there was no similar improvement trend with respect to maneuverability. Although security restrictions do not allow a complete quantitative expression of results for contemporary fighters, we can qualitatively express what has happened during the 1970s. The results suggest that the F-14A, which shares the TF30 engine with the F-111A, achieved its improved specific power and sustained load factor through mission tradeoffs (relative to the F-111A, the F-14A traded range performance for better maneuverability), whereas the F-15A and the F-16A improved these two parameters largely through absolute gains in performance brought about by technological advance.

Figure 10 suggests that range and payload fraction have undergone considerable fluctuations, probably a reflection of varying mission requirements. More generally, we can conclude that designers of contemporary fighter aircraft have incorporated considerable improvements in air-to-air combat performance (measured in terms of specific power and sustained load factor) without having to sacrifice much cruise performance (measured in terms of range and payload fraction). Because the design requirements for optimum air-to-air combat performance often conflict with requirements for satisfactory cruise performance, this represents a considerable achievement.

CHANGES IN THE RATE OF TECHNOLOGICAL ADVANCE

For the overall data sample, the log-linear equation form, implying a decelera-

[1] Figure 10 depicts the same information computed in Table 11 for just one aircraft, the F-106A. Figures H.1 and H.2 in Appendix H depict comparable information derived from technology Eqs. (2) and (3).

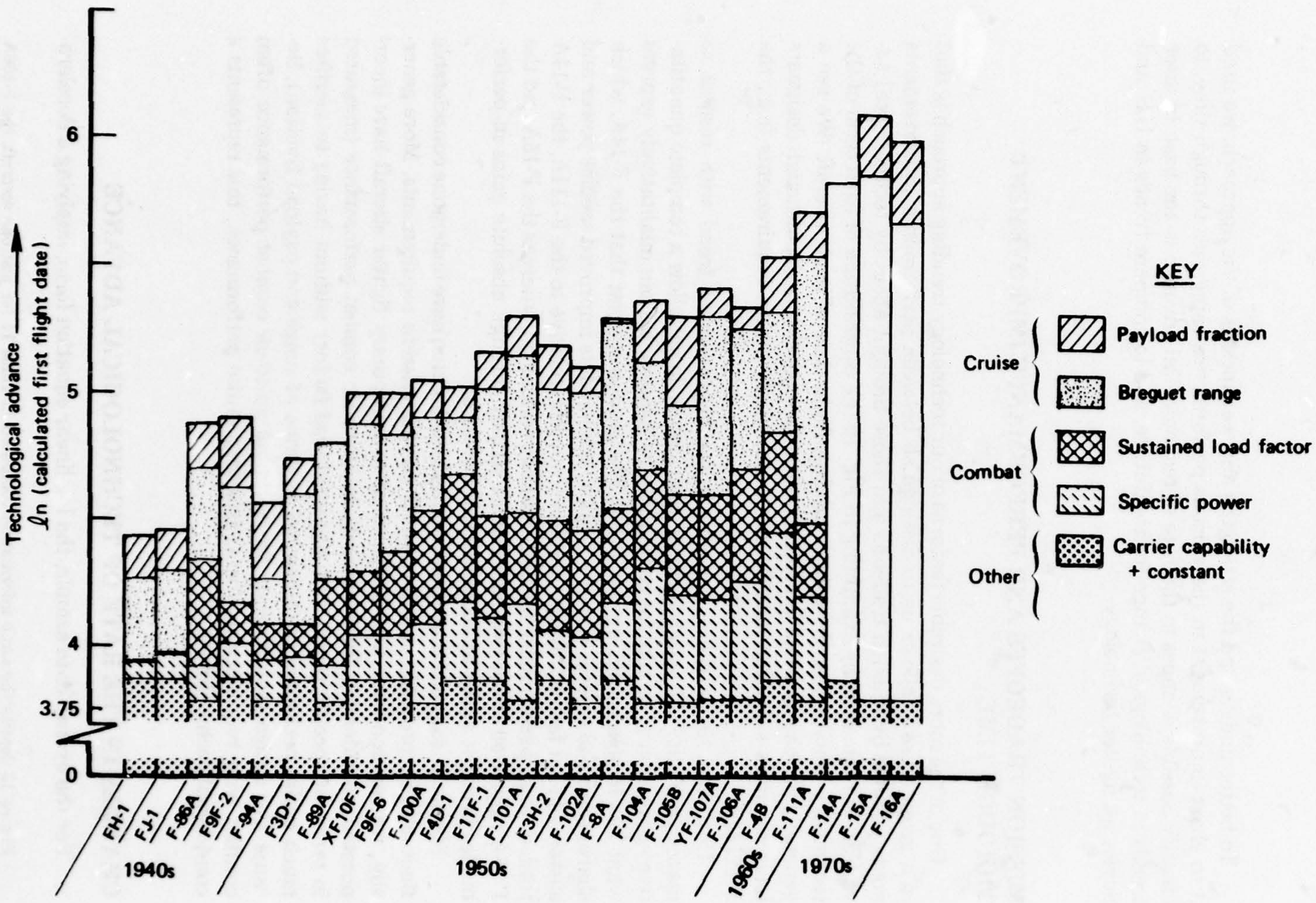

Fig. 10—Technological advance and mission tradeoffs measured by Eq. (1)

tion in technology, unambiguously described the growth in fighter technology better than the other equation forms. But we suspected that a possibly greater rate of technological advance may have prevailed through the mid-1950s, given the rapid rate of introduction of new fighter models between the late 1940s and the mid-1950s. We tested the hypothesis by estimating technology equations using the four equation forms for the first 17 aircraft in the sample, through flight of the F-104A, the first operational Mach 2 fighter. The results, shown in Table 18, were much more ambiguous for this sample of earlier aircraft.[2] The log-linear equation form generally had somewhat poorer statistical properties than the other forms. In this context, the other forms represent either a constant (linear-linear) or accelerating (log-log and linear-log) rate of technological advance. Although these results are far from conclusive, we suspect that air vehicle technology probably advanced at least at a constant rate through the mid-1950s.

Table 18

STATISTICAL PROPERTIES OF FOUR EQUATION FORMS FOR 17 NEW DESIGNS THROUGH FLIGHT OF THE F-104A

Equation Form[a]	R^2	SEE[b]	F Statistic	Durbin-Watson Statistic
Log-linear	.871	.122[c]	14.9	1.49
Linear-linear	.880	15.2	21.9	1.52
Log-log	.889	.113[d]	17.6	1.46
Linear-log	.882	15.1	22.4	1.42

[a]Independent variables: specific power, sustained load factor, Breguet range, payload fraction, carrier capability.

[b]Expressed in logarithmic terms or in months, depending on the equation form.

[c]SEE of .122 around mean first flight date corresponds to + 18.2, -16.1 months.

[d]SEE of .113 around mean first flight date corresponds to + 16.8, -15.0 months.

An earlier Rand application of this technology trending technique to aircraft turbine engines developed from the 1940s through the 1960s found the rate of technological advance for engines to be in an acceleration phase. At least we can infer that by their identification of the linear-log equation form as most satisfactory. [1] The data base supporting that analysis contained more than just fighter aircraft engines. More recently, we repeated the analysis but limited the data sample to engines used in fighter applications, up to and including the F100 engine used in the F-15A and F-16A. The results were conclusive enough to suggest that fighter engine technology is not decelerating. How long it can follow this trend in technological advance remains a point of conjecture.

[2] A comparison of residual scatterplots did not help in differentiating among equation forms.

TECHNOLOGICAL TRENDS FOR THE FUTURE

To assess some of the implications of an implied deceleration in the growth of air vehicle technology we (1) considered whether a weighting scheme enhanced the predictive properties of the technology equations, (2) used the equations to predict when designers might achieve improvements in air vehicle technology comparable to those in the past, and (3) characterized the uncertainties associated with those predictions.

Utility of Weighting

Because 80 percent of the aircraft in the data sample flew before 1957, we had some concern about whether the technology equations would give credible projections of future technological improvement. We considered several weighting schemes that emphasized the performance of the contemporary aircraft in the sample (the 20 percent having first flight dates after 1960). We ultimately selected an exponential weighting function that took into account the time intervals separating the aircraft flight events, particularly the big gap between 1956 and 1961 in our data base. After scaling the weighting function to place equal emphasis on the five aircraft that flew after 1957 and the 20 aircraft that flew before that year, we reestimated the technology equation.[3]

The coefficients of the weighted expression (see Table 19) not unexpectedly reflect the greater emphasis on range, payload, and maneuverability for the contemporary aircraft and the diminished emphasis on higher and higher speeds. Despite the differences in emphasis, the weighted and unweighted expressions yield similar projections. For example, Appendix F describes a case in which the unweighted equation predicts a flight date of late 1990, whereas the weighted expression predicts a mid-1989 flight date. The 90 percent confidence interval of 26 years dwarfs the 14-month difference in calculated first flight dates. In this context, weighting seems superfluous. Moreover, the large confidence intervals reinforce our previous observation that the technology equations seem suitable only for measuring gross trends in technology.

Implications of Technological Trend

To show the implications of the deceleration in the rate of technological advance, in Fig. 11 we have plotted the logarithm of the calculated first flight date as a function of the actual first flight date for each aircraft in the sample.[4] The solid line passing through the data points (analogous to the 45° line in Fig. 4) defines where the calculated first flight date equals the actual first flight date. This trend graphically depicts how the rate of improvement in basic air vehicle performance has diminished as technology has advanced. It has become increasingly difficult to sustain the rates of technological improvement that we have grown accustomed to in the past.

The conclusion of Century Series development represents a watershed of sorts in terms of a change in the rate of technological advance for fighter aircraft. From the mid-1940s to the mid-1950s, fighter aircraft performance improved rapidly and

[3] Appendix E describes development of the weighting scheme.

[4] Figures H.3 and H.4 in Appendix H present comparable results for technology Eqs. (2) and (3).

Table 19

COMPARISON OF COEFFICIENTS: WEIGHTED AND UNWEIGHTED EQUATIONS

Equation	Constant	Specific Power	Breguet Range	Sustained Load Factor	Payload Fraction	Carrier Capability
Unweighted[a]	3.88	.065	.406	1.41	.939	-.093
Weighted[b]	3.67	.045	.495	1.90	1.45	-.120

[a]For data sample of 25 new U.S. designs, each having equal weight (Eq. (1) from Table 10).

[b]For the data sample of 25 new U.S. designs, the last five aircraft collectively have the same weight as the first 20. See Appendix E.

the military services sponsored the introduction of many new fighter models.[5] The frequency of introduction of new aircraft designs slowed by the late 1950s as performance gains, which encompassed the move from high subsonic speeds to Mach 2, drove up costs (see Fig. 12). The rate of technological advance has become decidedly more measured during the 1960s and 1970s.

What do the present trends in technological advance portend for future fighter developments? With some important qualifying assumptions, we can use the technology equations to speculate about the answer to such a question. We assume that technical constraints, cost constraints, and external threat considerations comparable to those that influenced the trend established from the 1940s through the 1970s will pertain in the future. Moreover, we emphasize that the technology equations obviously reflect only the average rate of technological advance achieved by the development process, not what might be achieved by crash programs.

With these caveats in mind, we can return to Fig. 11 to estimate how much time might be required to improve the air vehicle performance of the F-15A, expressed in terms of specific power, sustained load factor, Breguet range, and payload fraction, by an amount equivalent to that experienced in moving from the F-4B to the F-15A. The trend defined by technology Eq. (1) suggests that based on past trends, with 90 percent confidence, the United States could achieve this improvement sometime between 1993 and 2033, with a calculated first flight date of 2011.[6] This result quantifies the deceleration in the rate of technological advance and highlights some of the uncertainty inherent in the development process. This performance improvement could require two to five times longer than was required in advancing from the level of technology of the F-4B to the F-15A.[7] As we reach higher and higher plateaus of air vehicle technology in the future, the improvements in technology could become more and more difficult to achieve.

[5] Did the intense design and flight activity of the 1950s act as a forcing function to prompt the rapid technological advance, or did recognition of opportunities to exploit new inventions, technologies, and scientific discoveries stimulate the flight activity? The rate of introduction of new fighter models and the rate of technological advance seem to correspond quite closely, but we cannot confidently distinguish between cause and effect.

[6] The careful reader of Fig. 11 will observe that although absolute improvement in the cruise and combat parameters is identical in going from the F-4B to the F-15A and from the F-15A to the hypothetical Air Force fighter, the increment along the vertical technological advance axis is not. The carrier capability of the F-4B accounts for the .093 unit difference.

[7] Although some of the numerical specifics change when results are derived from technology Eqs. (2) and (3), the conclusion remains the same (see Figs. H.3 and H.4 in Appendix H).

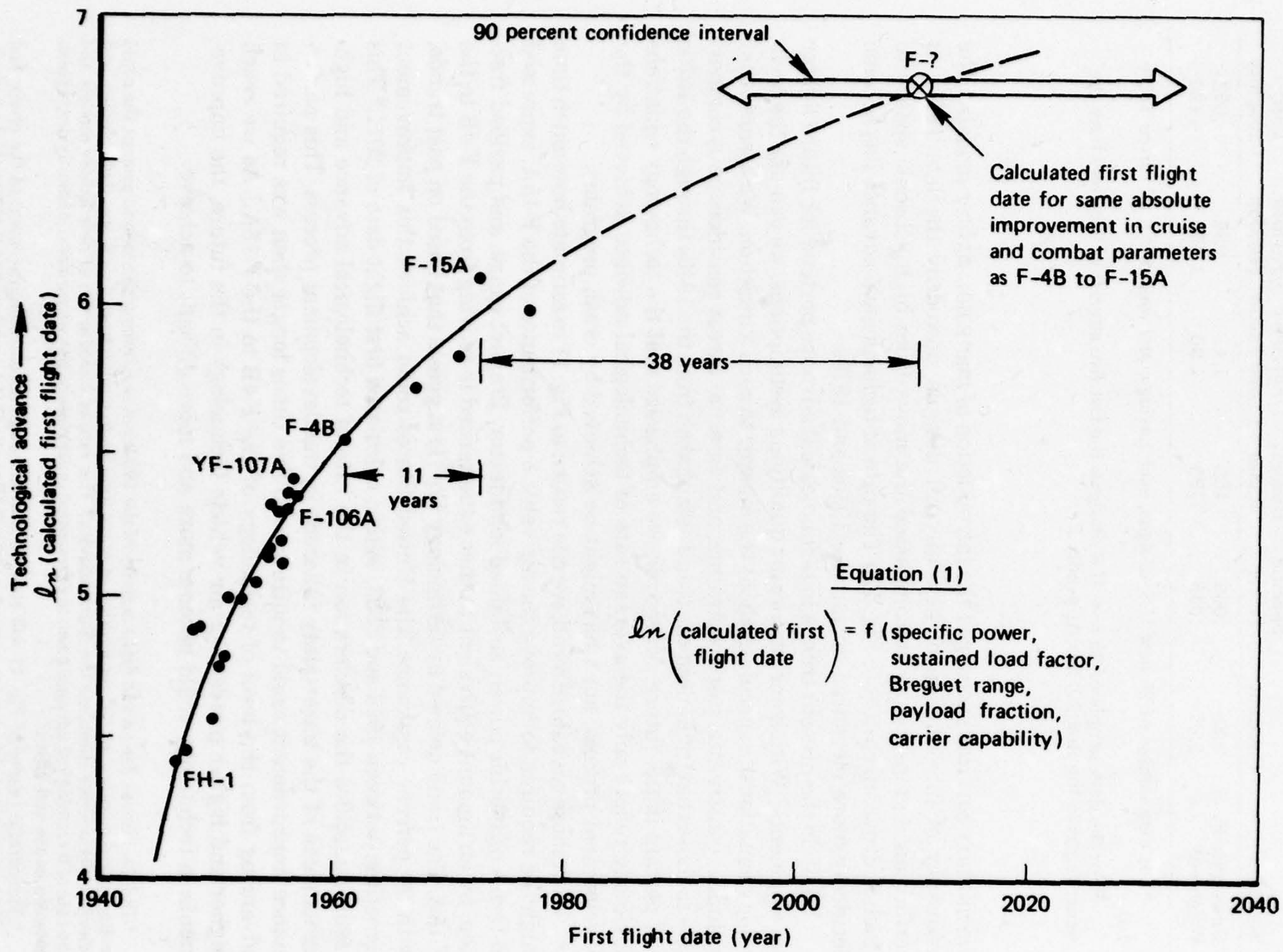

Fig. 11—Technology trend from Eq. (1)

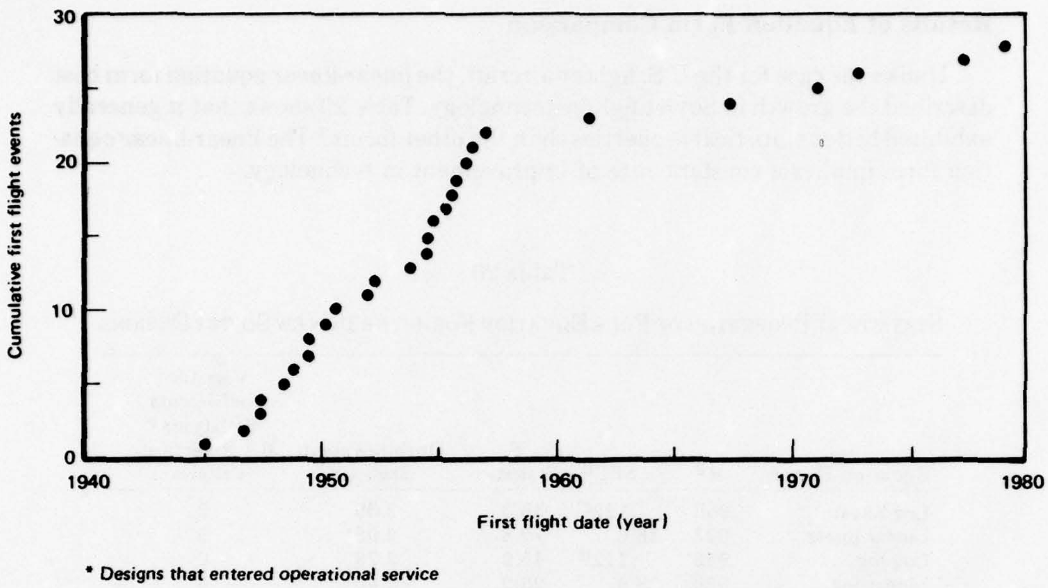

*Fig. 12—The rate of introduction of new U.S. designs**

The trend established through the F-15A—a decline in the rate of improvement in traditional air vehicle technology—could have important implications for future fighter aircraft development programs. The trend reflects the choices and realities of the development process, including an increasing emphasis today on cost as a constraint. We are not suggesting the trend is immutable—for some increase in expenditures, the military services can probably increase the rate of technological advance. But the cost of making substantial improvements in such traditional areas of air vehicle performance as specific power, maneuverability, range, and payload carriage may be very high. Perhaps aircraft designers will be able to improve combat effectiveness more easily through enhancements to armament, avionics, or stealth features. Although this analysis does not indicate where the greatest leverage exists, it does suggest that at the very least the aircraft designer should remain aware of these trends when balancing improvements in engine and airframe technology against improvements in the other technologies that also contribute to combat effectiveness.

COMPARISON OF U.S. AND SOVIET TECHNOLOGY TRENDS

To make comparisons between technological trends for U.S. and Soviet fighter aircraft, we assembled design and performance information for 13 new Soviet fighter designs from the mid-1940s to the early 1970s and developed technology equations in a manner analogous to that used for the U.S. fighter sample.

Results of Equation Form Comparison

Unlike the case for the U.S. fighter aircraft, the linear-linear equation form best described the growth in Soviet fighter technology. Table 20 shows that it generally exhibited better statistical properties than the other forms.[a] The linear-linear equation form implies a constant rate of improvement in technology.

Table 20

STATISTICAL PROPERTIES OF FOUR EQUATION FORMS FOR 13 NEW SOVIET DESIGNS

Equation Form[a]	R^2	SEE[b]	F Statistic	Durbin-Watson Statistic	Variable Coefficients Satisfying 0.1 Rejection Criteria
Log-linear	.950	.122[c]	38.3	2.05	2
Linear-linear	.973	18.0	72.8	2.08	3
Log-log	.958	.112[d]	45.9	2.73	2
Linear-log	.926	29.9	25.2	1.40	3

[a]Independent variables: specific power, sustained load factor, Breguet range, payload fraction.

[b]Expressed in logarithmic terms or in months, depending on the equation form.

[c]SEE of .122 around mean first flight date corresponds to +27.1, −24.0 months.

[d]SEE of .112 around mean first flight date corresponds to +24.7, −22.1 months.

Because the rate of growth in U.S. fighter technology seemed to parallel the rate of introduction of new fighter models, we were curious to see if the same pattern held true for the Soviets. Figure 13 suggests that this has indeed been the case. The frequency of introduction of new Soviet fighter models that have eventually entered service has followed a steady, methodical, linear trend that corresponds quite closely to the trend that best describes technological change in Soviet fighter aircraft (the linear-linear equation form).[b]

Soviet Technology Equations

Guided by our experience in developing the U.S. technology equations, we developed the set of Soviet fighter aircraft equations shown in Table 21, each of which uses the linear-linear equation form. The equations include parameters that measure speed, range, and payload performance. The first three do not measure maneuver capability. None includes the carrier capability variable, because our Soviet sample includes only land-based aircraft. It is not surprising that the equations suggest the importance of maximum speed capability in the form of the specific power parameter. To permit higher and higher speeds, the Soviets have

[a] This conclusion also holds true for other sets of variables.

[b] As in the U.S. case, we cannot confidently distinguish between cause and effect when comparing trends in the rate of flight activity and technological advance.

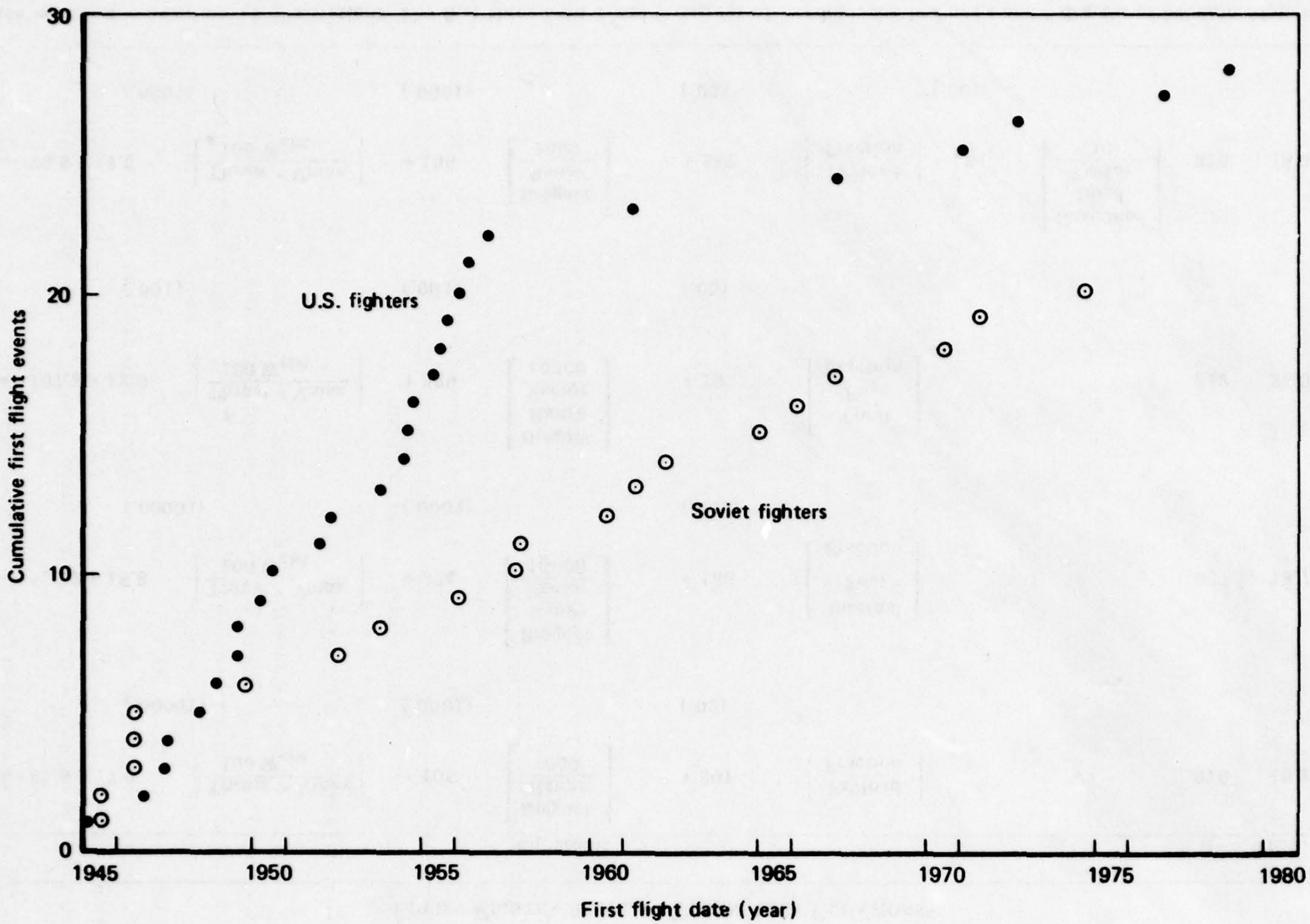

Fig. 13—Comparison of U.S. and Soviet first flight activity

Table 21

SOVIET FIGHTER AIRCRAFT TECHNOLOGY EQUATIONS[a]

	Equations	R^2	SEE	F
(7)	$t = -57.8 + 17.9 \left\lvert \frac{\text{Thrust} \cdot \text{Vmax}}{100\, W_{cbt}} \right\rvert + 105 \left[\frac{\text{Breguet Range}}{1000} \right] + 301 \left\lvert \text{Payload Fraction} \right\rvert$	.970	18.1	95.9
	(.00001) (.0001) (.02)			
(8)	$t = -129.2 + 18.8 \left\lvert \frac{\text{Thrust} \cdot \text{Vmax}}{100\, W_{cbt}} \right\rvert + 374 \left[\frac{\text{Breguet Range Factor}}{10000} \right] + 186 \left[\text{Internal Fuel Fraction} \right]$	.967	18.7	89.2
	(.00001) (.0001) (.005)			
(9)	$t = -107.3 + 18.8 \left\lvert \frac{\text{Thrust} \cdot \text{Vmax}}{100\, W_{cbt}} \right\rvert + 329 \left[\frac{\text{Breguet Range Factor}}{10000} \right] + 132 \left[\text{Total Fuel Fraction} \right]$	.942	25.0	49.0
	(.001) (.001) (.05)			
(10)	$t = -99.9 + 17.5 \left\lvert \frac{\text{Thrust} \cdot \text{Vmax}}{100\, W_{cbt}} \right\rvert + 105 \left[\frac{\text{Breguet Range}}{1000} \right] + 287 \left\lvert \text{Payload Fraction} \right\rvert + 134 \left[\frac{\text{Sustained Load Factor}}{10} \right]$	.973	18.0	72.8
	(.0001) (.0001) (.05) (.50)			

[a]Each equation is based on 13 observations. The first three have 3 and 9 degrees of freedom, the last has 4 and 8 degrees of freedom. Upper bound for risk of incorrectly rejecting the null hypothesis that a coefficient is really zero is shown in parentheses below the coefficients. Refer to Appendixes A and B for full variable definitions. t = calculated first flight date measured in months since January 1, 1940.

introduced a succession of design innovations not unlike those in the United States —swept wings, afterburning turbojets, delta wings, variable geometry engine inlets, etc.

The remaining variables describe, in alternative ways, the range and payload performance of Soviet fighters. The sample has considerable variability in these parameters because early Soviet fighters had a historically defensive role that did not require exceptional range or payload performance. More recent Soviet fighter designs exhibit greater payload capability. Variable geometry wings have contributed to better range performance.

The Soviets have consistently designed highly maneuverable aircraft. As a result, there is only a 1.4 g difference between the lowest and highest sustained load factor in the sample. We suspect this contributed to the difficulty in establishing a statistically identifiable trend for maneuverability. Some alternative variable selections to measure maneuverability were not successful. Although it did not pass our rejection criteria, we included a fourth equation (Eq. (10)), which incorporated the sustained load factor as a variable. This provided a means to compare U.S. and Soviet technology trends on a consistent basis using the same four performance attributes.

Comparing Trends in U.S. and Soviet Fighter Technology

Using the trend equations developed separately for U.S. and Soviet aircraft, we compared gross trends in performance and found no readily discernible long-term differences in the basic air vehicle performance exhibited by U.S. and Soviet fighter aircraft, at least when measured by the four parameters shown in Fig. 14. To obtain these results, we inserted Soviet aircraft characteristics into the American trend equation in Fig. 14(a), and did the opposite in Fig. 14(b).[10] In each case, we fitted simple least squares lines through the data points to make long-term comparisons easier.[11]

The rationale used to interpret the results deserves some explanation. After establishing a technology trend for the 25 U.S. aircraft whose data points (not shown) are distributed around the solid 45° line, we inserted the parameters of the 13 Soviet aircraft into the U.S. technology equation (see Fig. 14 (a)). Comparison of the calculated first flight date (an expectation of when the United States could have achieved this technology) with the actual first flight date achieved by the Soviets indicated whether one country enjoyed an apparent advantage in basic air vehicle technology. In actuality, we did not attach great significance to any single data point but rather fitted a line through all the data points to assist in comparing the Soviet and U.S. experiences represented by the 45° line. In Fig. 14(b), the same

[10] This technique yielded intuitively plausible and generally explainable results, giving us more confidence in the reliability of the technology equations developed from the small U.S. and Soviet data samples. Ideally, of course, to check the reliability of the equations, we would have preferred using other independent and equivalent samples of fighter aircraft from which we could estimate new equation coefficients to compare with those developed from the original samples. We obviously did not have that option, so the evaluation of new Soviet fighter designs in the U.S. equation and vice versa was an imperfect but pragmatic second choice for checking whether the results obtained from the equations made sense when used with independent data samples.

[11] Rather than replotting all the data points for the U.S. aircraft in Fig. 14(a) and the data points for Soviet aircraft in Fig. 14(b), we show only the 45° lines about which their data points are distributed.

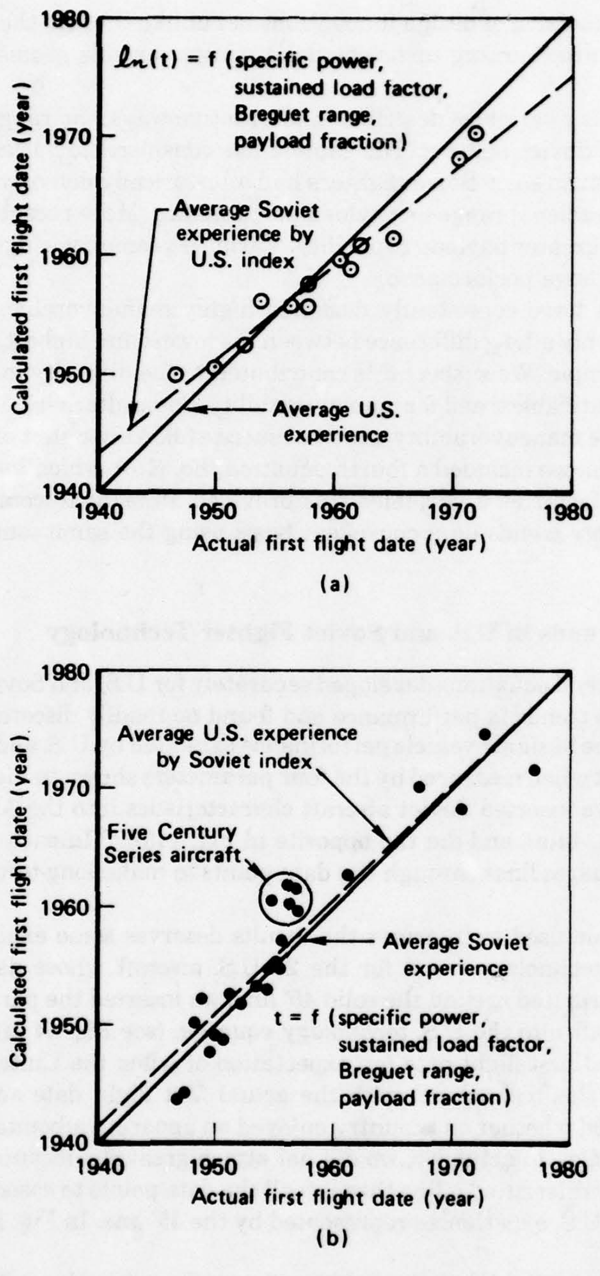

Fig. 14—Comparison of U.S. and Soviet fighter technology trends

general rationale applies, although the interpretation is reversed as we inserted U.S. aircraft parameters into the Soviet technology equation.

The trend line fitted through the Soviet data points in Fig. 14(a) is slightly less than 45° and hints at a slight U.S. technology advantage beginning around the mid-1950s, a period of intense U.S. fighter development activity. An earlier Rand study using the same approach as in this analysis compared trends in U.S. and Soviet aircraft turbine engine technology development and found a similar advantage for the United States beginning in the early to mid-1950s.[1] Obvious uncertainties associated with the Soviet data base and inherent uncertainties in the technique itself, already demonstrated, make us reluctant to attach any great significance to this modest U.S. advantage in air vehicle technology.

Figure 14(b) suggests the United States may have had a modest short-term advantage during the mid-1950s, reflected by the cluster of five Century Series fighter aircraft[12] above the Soviet trend line during this period. But overall the U.S. trend line almost coincides with the Soviet trend line in Fig. 14(b); neither country seems to hold a dominant long-term advantage in air vehicle technology.

A comparison of Figs. 14(a) and 14(b) also reveals a modest inconsistency in the results of the technology comparison. From Fig. 14(a), we would expect the U.S. performance trend line to have a somewhat steeper slope than the Soviet line in Fig. 14(b), but it does not. The so-called "index number problem" that can occur when two countries with different histories of industrial and technological development exhibit different patterns of technological progress may be partly responsible for the inconsistent result. An index of technology based on the experience of one country may rank two aircraft differently than a similar index developed according to the experience of another country. We suspect that to a lesser degree the index number problem and to a greater degree the generally comparable performance exhibited by aircraft of both countries over the long run share responsibility for the apparent inconsistency.

This apparent similarity in performance trends suggests that if they desire to do so, the Soviets have the technological capability to develop an air superiority fighter having air vehicle performance comparable to that exhibited by contemporary U.S. aircraft (at least when measured in terms of specific power, sustained load factor, Breguet range, and payload fraction). Whether this comparability extends to other important features of the fighter aircraft weapon system such as avionics and armament systems is beyond the scope of this analysis.

[12] The aircraft include the F-101A, F-104A, F-105B, F-106A, and the YF-107A.

VI. OBSERVATIONS

This attempt to measure technological change in jet fighter aircraft has identified parameters that at least partially describe the performance consequences of some important advances in U.S. and Soviet technology during the past 30 years. The parameters describe speed, maneuverability, range, and payload performance. Tracing the development history of U.S. and Soviet fighter aircraft confirms that the desire to improve performance in these areas has stimulated major technological innovations (e.g., swept wings, delta wings, variable geometry wings, afterburners, turbofan engines).

Statistical expressions relating the time of appearance of an aircraft design to key performance parameters describe some (but certainly not all) aspects of basic air vehicle performance. Although this study is only a first attempt at developing and applying this technique to the analysis of fighter aircraft, several chronic problems may frustrate subsequent efforts to improve the precision and descriptiveness of the statistical expressions. These obstacles include a small data sample of aircraft, an uneven distribution of those aircraft through time, and a historically broad definition for what constitutes a fighter aircraft, making it difficult to develop parameter sets that describe all the major attributes of each fighter.

Despite these limitations, the approach has proved useful in identifying parameters that describe air vehicle technology, in distinguishing between performance enhancements made possible by mission tradeoffs and those brought about by technological advance, and in describing gross trends in the rate of advancement of fighter technology. The approach provided useful insights about the comparative rate of technological advance exhibited by new and derivative designs, the rate of growth in U.S. fighter technology through time and implications for the future, and the comparison of trends in U.S. and Soviet fighter technology. It also has qualities that may make it a useful tool for evaluating the technological risk of new fighter aircraft concepts.

If we build on the initial development and application of this approach for measuring technological change in fighter aircraft, what refinements and extensions to the analysis could we contemplate? One aerospace industry executive expects the rate of expansion of the flight envelope to continue to slow down. "Future technology will be applied primarily within the present operating envelope to realize a much more dynamic use of that envelope."[13]

Such a trend may require a reorientation in parameter selection. Point performance parameters such as specific power and sustained load factor may not adequately characterize changes in technology. If one considers specific excess power as the third dimension of the altitude-speed envelope, then the integrated volume of the envelope might measure one meaningful aspect of technological advance. How well an aircraft converts specific excess power into turning performance depends upon its aerodynamics; hence, one would have to evaluate the volume of the flight envelope under some sustained load factor to measure turning capability. This approach would have the further advantage of quantifying the sustained supersonic maneuvering capability of contemporary jet fighters and perhaps provide a more general measure of improvements in aircraft handling characteristics.

We selected and defined the parameters used in this report to measure the important attributes of fighter aircraft performance. Some tests using a limited sample of bomber and attack aircraft suggested that the fighter technology equations did not satisfactorily measure the level of technology of these aircraft types. However, this limited analysis did not allow us to conclusively evaluate whether aircraft designers draw from the same common source of aviation technology or different sources for the different aircraft types, nor did it allow us to confirm or refute the wisdom of limiting the present analysis to a single class of aircraft. Answers to such questions would require an expansion of the data base to include more attack aircraft and bombers and consideration of alternative parameter sets selected to measure a broader set of aircraft attributes.

Finally, the ultimate objective of coupling fighter performance and costs in an integrated model remains a highly desirable but as yet unachieved objective. Existing airframe cost models are not very sensitive to the diversity of air vehicle performance attributes or program characteristics that can influence costs. The present form of the technology equation does not explicitly include considerations of cost. For example, it does not recognize the influence of design-to-cost procedures or the technology associated with lowering costs while keeping performance constant. Preliminary attempts to integrate the performance trending approach with airframe cost models have not met with success, but the potential value of such an integrated model dictates that we remain open to new ideas for achieving this elusive goal.

Appendix A

U.S. AIRCRAFT DESIGN AND PERFORMANCE CHARACTERISTICS

This appendix contains the aircraft design and performance parameters used in the analysis of U.S. aircraft (see Table A.1), followed by definitions of the parameters.[1] The appearance of an asterisk (*) indicates an unknown data value. We have not included some F-14A, F-15A, and F-16A parameters for reasons of security. Abbreviations used in Table A.1 are defined below.

LBS . . . . . pounds
PSF . . . . . pounds per square foot
FT . . . . . . feet
FT2 . . . . . square feet
FPM . . . . . feet per minute
NMI . . . . . nautical miles
KTS . . . . . knots
HP . . . . horsepower
M . . . . . Mach number
G . . . . . acceleration of gravity
SL . . . . sea level
NEW . . new design
A-T-G. . air-to-ground mission emphasis

[1] We primarily used engineering documents such as manufacturers' performance substantiation reports and personal communications with manufacturers to construct the data base.

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Table A.1

U.S. Jet Fighter Design and Performance Characteristics

AIRCRAFT TYPE	FIRST FLIGHT DATE	EARLY FIRST FLIGHT DATE	STRESS DESIGN WEIGHT (LBS)	ULTIMATE LOAD FACTOR (G'S)	STRUCTURE WEIGHT (LBS)	EMPTY WEIGHT (LBS)	ADJUSTED EMPTY WEIGHT (LBS)	MAXIMUM GROSS WEIGHT (LBS)	FULL FUEL WEIGHT (LBS)	FULL INTERNAL WEIGHT (LBS)	COMBAT WEIGHT (LBS)	WEIGHT INTERNAL FUEL (LBS)
FH-1	82	61	9800	11.25	3810	6700	6613	11952	11952	9970	9070	2250
FJ-1	89	83	10800	10.50	4250	8590	8783	14865	14865	12570	11460	2775
F-86A	101	94	13400	11.00	4840	10040	10040	17186	17186	14140	12980	2900
F2H-1	104	61	14000	11.25	4980	9700	9587	16201	16200	16200	14100	5250
F9F-2	107	95	13470	11.25	4890	8738	8629	19494	16450	14125	12486	4097
F-94A	115	49	13800	11.00	4670	9790	9790	18830	15705	13210	12380	2075
F-86D	120	94	13400	11.00	5930	13080	13080	19515	19515	17750	16170	3950
YF-93A	121	94	21850	11.00	8050	15390	15390	27791	27790	27790	23550	10600
F3D-1	122	99	18100	9.00	7480	14860	16220	28800	26627	24490	21250	8100
F-89A	127	104	32400	8.50	12930	23870	26809	36541	36540	36540	32510	10075
XF10F-1	137	137	26160	11.25	12550	20550	20265	35450	35370	31300	27500	9500
F-89C	141	104	32400	8.50	13480	25100	28164	43310	37752	37800	33720	10200
F-94C	142	49	15000	13.00	5800	12620	11565	24184	22972	16120	15160	2400
F9F-6	147	95	15600	11.25	6240	11060	10918	21300	20709	17998	15797	5502
F2H-3	148	61	18600	9.75	6800	13310	14083	26165	23393	21000	18410	6475
F-84F	155	74	18500	14.00	7320	13650	11654	27134	26798	18710	17190	3800
F-86H	160	94	19010	11.00	6230	13580	13580	24300	23458	18650	17180	3675
F-100A	166	161	24000	11.00	9710	18260	18260	29010	29010	25010	23050	4900
FJ-3	168	94	16480	9.75	6240	12190	12899	23906	19987	17010	15550	3650
F4D-1	174	133	18200	9.50	7490	16050	17071	28000	25520	21030	19500	3825
F11F-1	175	175	16500	9.75	7240	13100	14025	23459	22537	20110	17740	5925
F-101A	177	106	37000	11.00	9760	24720	24720	48803	46678	40430	34850	13950
FJ-4	182	94	16500	9.75	7940	13440	14342	24191	23103	20020	17830	5475
F3H-2	184	140	26000	11.25	10880	21270	21023	39000	36268	32040	28120	9800
F-102A	187	166	25500	10.50	8910	19460	19865	31096	31096	27970	25240	6825
F-8A	189	183	*	9.60	*	15510	*	27500	27280	27280	23970	8275
F-104A	194	170	15200	11.00	5600	11570	11570	23526	23526	17610	15640	4925
F5U-1	196	133	19630	10.50	8450	16550	16934	29143	29143	26860	23350	8775
F-105B	197	190	27000	13.00	13460	24500	22053	53000	45843	33600	30530	7675
YF-107A	201	201	31860	11.00	12830	24100	24100	41537	41537	37150	32730	11050
F-106A	204	166	29780	10.50	10270	23180	23647	36395	36395	33160	29940	8050
F-104G	250	170	19150	11.00	6620	14050	14050	29038	26842	21880	19230	6625
F-4B	255	221	34950	12.75	12950	27530	25470	56000	54434	43590	38170	13550
F-4C	281	221	37500	12.75	13490	28540	26394	59700	53797	43900	38780	12800
F-5A	286	232	11620	11.00	4740	8130	8130	20336	17888	13705	12189	3790
F-111A	328	300	70000	11.00	26170	46170	46170	98850	98850	80380	67280	32750
F-14A	372	372			19750	36825	39069					
F-15A	392	392	37100	11.00	13108	26795	24810	53430	53430	39740	35140	11500
F-16A	444	410	22500		6718	14062	12818	33000	31107	22197	19423	6935

Table A.1-continued

AIRCRAFT TYPE	WEIGHT EXTERNAL FUEL (LBS)	STRUCTURAL EFFICIENCY	WING AREA (FT2)	WETTED AREA (FT2)	ASPECT RATIO	MAXIMUM LIFT-DRAG RATIO	STATIC THRUST (SL) (LBS)	MAXIMUM SPEED (KTS)	MAXIMUM SPEED (SL) (KTS)	MAXIMUM SPECIFIC POWER (HP/LB)	MAXIMUM SPECIFIC ENERGY (FT)
FH-1	1770	.0346	274	1070	6.1	17.5	3200	416	406	0.45	46300
FJ-1	2040	.0375	255	*	5.7	14.9	3880	474	462	0.49	51600
F-86A	2767	.0328	288	1070	4.8	15.0	4770	590	585	0.67	59500
F2H-1	0	.0316	294	*	5.9	15.4	6300	513	513	0.70	57100
F9F-2	1440	.0323	250	*	5.8	*	5000	513	513	0.63	57100
F-94A	2145	.0308	234	1182	6.4	16.7	5930	515	510	0.76	55300
F-86D	1560	.0402	288	1201	4.8	13.0	6720	601	601	0.77	*
YF-93A	0	.0335	306	*	4.9	14.0	7750	607	606	0.61	60400
F3D-1	1800	.0459	401	1843	6.2	15.3	5850	470	464	0.40	47700
F-89A	0	.0469	606	*	4.4	18.2	13000	546	475	0.67	*
XF10F-1	3600	.0426	467	*	5.5	*	10900	612	612	0.74	57900
F-89C	0	.0489	606	*	4.4	18.2	14300	545	475	0.71	*
F-94C	6240	.0297	233	1227	6.1	13.8	7900	560	560	0.90	63200
F9F-6	1800	.0356	300	1172	4.0	*	7250	568	565	0.80	58400
F2H-3	2040	.0375	294	*	5.9	15.4	6500	513	513	0.56	52100
F-84F	5980	.0283	325	1410	3.5	12.9	7220	590	590	0.76	56000
F-86H	4160	.0298	313	1195	4.9	14.5	9030	595	595	0.96	*
F-100A	3575	.0368	385	1509	3.9	13.6	14000	752	660	1.40	64400
FJ-3	2600	.0388	302	1130	4.6	14.2	7250	592	592	0.85	61400
F4D-1	3900	.0433	557	1600	2.0	10.0	14245	628	627	1.41	64500
F11F-1	1950	.0450	250	1242	3.9	10.4	9800	655	655	1.11	64700
F-101A	5850	.0240	368	2060	4.3	10.0	23400	872	653	1.80	77700
FJ-4	2600	.0494	339	1177	4.5	14.4	7250	591	591	0.74	60700
F3H-2	3666	.0372	519	1908	2.4	12.1	13100	622	622	0.89	58700
F-102A	2990	.0333	662	2170	2.2	11.3	14400	680	634	1.19	65700
F-8A	0	*	375	*	3.4	12.9	12400	880	637	1.40	71200
F-104A	5540	.0335	196	1078	2.4	10.2	11000	1150	721	2.48	117000
F5D-1	1950	.0410	557	1643	2.0	10.0	14300	751	649	1.41	63400
F-105B	11050	.0383	385	*	3.2	11.1	17850	1112	714	2.00	93000
YF-107A	4897	.0366	376	1836	3.6	12.9	17850	1115	774	1.87	91000
F-106A	2860	.0328	695	2230	2.2	12.2	18450	1153	707	2.18	99000
F-104G	4745	.0314	196	*	2.4	10.2	12000	1153	750	2.21	112000
F-4B	9112	.0291	530	2150	2.8	10.7	26700	1222	760	2.62	110000
F-4C	8710	.0282	530	2150	2.8	10.5	26700	1193	760	2.52	108000
F-5A	3549	.0371	170	*	3.8	10.2	6024	777	655	1.18	65600
F-111A	14028	.0340	525	2580	7.6	15.5	33700	1262	793	1.94	126000
F-14A			565	3155	7.3		34400				
F-15A	11700	.0321	608	2646	3.0						
F-16A	7974	.0221	300	1390	3.0	11.4					

Table A.1-continued

AIRCRAFT TYPE	CLIMB RATE (SL) (FPM)	CLIMB SPEED (SL) (KTS)	COMBAT CEILING (FT)	SERVICE CEILING (FT)	SUSTAINED LOAD FACTOR (G'S)	THRUST TO WEIGHT RATIO	WING LOADING (PSF)	INST. LOAD FACTOR (G'S)	BREGUET RANGE FACTOR (NMI)	BREGUET RANGE (NMI)	INTERNAL FUEL FRACTION	TOTAL FUEL FRACTION
FH-1	4810	274	40000	45000	0.10	.353	33	*	3300	688	.291	0.507
FJ-1	5100	280	42000	43500	0.10	.339	44	*	3640	752	.283	0.479
F-86A	7650	374	44500	47500	2.90	.367	45	5.6	4870	900	.258	0.492
F2H-1	7110	325	47400	49300	1.00	.447	47	*	3720	1456	.479	0.479
F9F-2	6100	*	43000	47000	1.10	.400	49	*	4720	1113	.409	0.507
F-94A	8650	340	46500	47800	1.00	.479	52	*	4110	479	.186	0.367
F-86D	12000	*	47800	49200	3.50	.416	56	*	3740	845	.286	0.393
YF-93A	9100	500	47200	48650	2.60	.329	76	3.1	4430	2127	.617	0.617
F3D-1	4100	281	36700	40500	0.90	.275	52	*	3750	1238	.494	0.592
F-89A	11800	*	48000	50000	2.40	.400	53	*	3970	1280	.381	0.381
XF10F-1	13200	*	45800	46500	1.80	.396	58	*	4650	1450	.436	0.588
F-89C	11100	*	47000	49000	2.30	.424	55	*	3970	1066	.370	0.370
F-94C	12000	425	52800	54900	2.90	.521	65	5.7	3800	397	.175	0.603
F9F-6	5900	*	45000	47500	2.30	.459	52	*	3840	1147	.440	0.545
F2H-3	5930	376	41900	43450	1.00	.353	62	*	4490	1276	.446	0.572
F-84F	7370	395	43000	44700	3.20	.420	52	6.8	4910	740	.255	0.575
F-86H	14000	483	50800	52600	3.40	.526	54	5.0	6350	1041	.245	0.502
F-100A	25700	565	52500	53200	3.20	.607	59	4.9	4920	910	.244	0.413
FJ-3	8500	360	49000	50400	3.10	.466	51	6.1	5990	992	.273	0.455
F4D-1	20200	*	54200	55000	3.50	.731	35	5.9	3820	561	.222	0.434
F11F-1	16400	*	50000	50600	2.80	.552	70	*	4320	1257	.418	0.537
F-101A	29600	596	50600	50900	2.50	.671	94	3.3	4530	1525	.527	0.737
FJ-4	7660	430	46800	48400	2.70	.407	52	5.8	5850	1501	.376	0.537
F3H-2	13000	496	46900	48050	3.00	.466	54	4.5	4480	1296	.441	0.591
F-102A	18700	600	51800	52800	3.00	.571	38	7.0	5390	1335	.323	0.461
F-8A	17300	*	51500	52500	2.64	.517	63	4.8	4990	1786	.435	0.435
F-104A	51500	612	58600	59000	2.70	.703	79	3.3	4500	1057	.388	0.801
F5D-1	22700	612	51200	51800	2.80	.612	41	6.2	4420	1583	.485	0.582
F-105B	38300	595	50200	50800	2.90	.585	79	3.8	5200	813	.296	0.691
YF-107A	36700	620	51900	52600	2.90	.545	87	3.6	5650	1747	.423	0.623
F-106A	34500	612	53700	54400	3.20	.616	43	6.1	5400	1349	.321	0.428
F-104G	44800	612	57500	57800	2.90	.624	98	3.0	3820	989	.434	0.735
F-4B	40600	*	56700	57000	2.90	.700	72	3.4	4200	1163	.451	0.713
F-4C	40000	595	54800	55500	3.00	.688	73	3.4	3840	926	.412	0.666
F-5A	22250	595	48800	49600	2.60	.494	71	4.5	3500	721	.382	0.696
F-111A	12600	628	55500	56000	2.00	.501	128	2.2	6450	2595	.688	0.898
F-14A												
F-15A							57				.407	0.767
F-16A							64				.454	0.920

Table A.1-continued

AIRCRAFT TYPE	PAYLOAD FRACTION	USEFUL LOAD FRACTION	RANGE × PAYLOAD FRACTION (LB-NMI/LB)	CARRIER CAPABILITY (NO=1)	SPEED CLASS (M<1=1)	DESIGN CLASS (NEW=1)	MISSION (A-T-G=1)	VARIABLE GEOMETRY (YES=1)	DESIGN LAG (MONTHS)	DESIGN ANTECEDENT (YES=0)
FH-1	.166	0.439	114	0	1	1	0	0	21	0
FJ-1	.154	0.422	116	0	1	1	0	0	6	0
F-86A	.177	0.416	159	1	1	1	0	0	7	0
F2H-1	.000	0.401	0	0	1	0	0	0	43	0
F9F-2	.275	0.552	306	0	1	1	0	0	12	0
F-94A	.298	0.480	143	1	1	1	0	0	66	0
F-86D	.090	0.330	76	1	1	0	0	0	26	0
YF-93A	.000	0.446	0	1	1	0	0	0	27	0
F3D-1	.150	0.484	185	0	1	1	0	0	23	0
F-89A	.000	0.347	0	1	1	1	0	0	23	0
XF10F-1	.117	0.420	169	0	1	1	0	1	0	1
F-89C	.127	0.420	135	1	1	0	0	0	37	0
F-94C	.333	0.478	132	1	1	0	0	0	93	0
F9F-6	.155	0.481	177	0	1	1	0	0	52	0
F2H-3	.197	0.491	251	0	1	0	0	0	87	0
F-84F	.310	0.497	229	1	1	0	1	0	81	0
F-86H	.233	0.441	242	1	1	0	1	0	66	0
F-100A	.138	0.371	125	1	0	1	0	0	5	0
FJ-3	.288	0.490	286	0	1	0	0	0	74	0
F4D-1	.249	0.427	139	0	1	1	0	0	41	0
F11F-1	.143	0.442	179	0	0	1	0	0	0	1
F-101A	.172	0.493	261	1	0	1	0	0	71	0
FJ-4	.172	0.444	258	0	1	0	1	0	88	0
F3H-2	.178	0.455	231	0	1	1	0	0	44	0
F-102A	.101	0.374	134	1	0	1	0	0	21	0
F-8A	.008	0.436	14	0	0	1	0	0	6	0
F-104A	.251	0.508	265	1	0	1	0	0	24	0
F5D-1	.078	0.432	124	0	0	0	0	0	63	0
F-105B	.366	0.538	297	1	0	1	1	0	7	0
YF-107A	.106	0.420	184	1	0	1	1	0	0	1
F-106A	.089	0.363	119	1	0	1	0	0	38	0
F-104G	.247	0.516	243	1	0	0	0	0	80	0
F-4B	.222	0.508	257	0	0	1	0	0	34	0
F-4C	.265	0.522	245	1	0	0	0	0	60	0
F-5A	.326	0.600	235	1	0	0	0	0	54	0
F-111A	.187	0.533	485	1	0	1	1	1	28	0
F-14A				0	0	1	0	1	0	1
F-15A	.256	0.499		1	0	1	0	0	0	1
F-16A	.327	0.574		1	0	1	0	0	34	0

DEFINITIONS OF DESIGN AND PERFORMANCE PARAMETERS

First Flight Date. The first flight date measured in months since January 1, 1940.

Early First Flight Date. The first flight date of the original hardware antecedent from which the subject design was derived, measured in months since January 1, 1940. This date is the same as the first entry if the design was a new model not directly traceable to any earlier model.[2]

Stress Design Weight. The aircraft weight used to describe the maximum stress condition the aircraft will undergo at the design ultimate load factor.

Design Ultimate Load Factor. The maximum load factor the aircraft is designed to withstand at the stress design weight without structural failure.

Structure Weight. The data entry on line 57 of the standard group weight statement document.

Empty Weight. The weight of the aircraft with no fuel, ordnance, or crew aboard.

Adjusted Empty Weight. An approximation of the empty weight of the aircraft if its design load factor were 11.0 gs.

Maximum Gross Weight. The maximum allowable gross takeoff weight.[3]

Full Fuel Weight. The weight of the aircraft with a full load of internal and external fuel.

Full Internal Weight. The weight of the aircraft with full internal fuel, full internal ordnance, and a full crew aboard.[4]

Combat Weight. The full internal weight of the aircraft less the weight of 40 percent of its internal fuel.

Weight Internal Fuel. The weight of usable fuel carried internally.

Weight External Fuel. The weight of usable fuel carried in external tanks.

Structural Efficiency. The structure weight divided by the product of the stress design weight and the design ultimate load factor.

Wing Area. The reference area of the wing.

Wetted Area. The total surface area of the aircraft.

Aspect Ratio. The ratio of the wingspan squared to the wing area.

Maximum L/D. The maximum lift-to-drag ratio of the aircraft in a clean configuration.

Static Thrust. The maximum installed static thrust at sea level with all engines operating.

Maximum Speed. The maximum sustainable speed, at whatever altitude it occurs, for the combat weight loading condition.

Maximum Speed (SL). The maximum speed at sea level.

Maximum Specific Power. The product of the maximum installed sea-level static thrust and the maximum velocity divided by the combat weight expressed in units of horsepower per pound.[5]

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[2]See Secs. II and III and Appendix C for additional discussion.

[3]If not available, we used the takeoff weight for the maximum weapon or fuel loading condition.

[4]We also include the weight of missiles and launchers for contemporary aircraft in which air-to-air missiles constitute an integral part of the armament package (e.g., recessed missile wells for four Sparrows on F-14s and F-15s, wing tip launchers for Sidewinders on F-16s).

[5]Shortcomings in the data base prevented a more rigorous calculation. Recognize that this approach does not account for those aircraft limited by some factor other than thrust at the

Maximum Specific Energy. The maximum value of the sum of kinetic and potential energy the aircraft develops in one g level flight divided by combat weight.

Climb Rate (SL). The maximum rate of climb at sea level in ft/min for the full internal weight loading condition.

Climb Speed (SL). The speed that yields the maximum climb rate at sea level with all engines operating at maximum power for the full internal weight loading condition.

Combat Ceiling. The altitude at which the aircraft can maintain a positive 500 ft/min rate of climb for the combat weight loading condition.

Service Ceiling. The altitude at which the aircraft can maintain a positive 100 ft/min rate of climb for the combat weight loading condition.

Sustained Load Factor. The maximum load factor the aircraft can sustain in level flight at an altitude of 25,000 ft and a Mach number of .8 at its combat weight.

Thrust-to-Weight Ratio. Ratio of the maximum sea level static installed thrust to the combat weight.

Wing Loading. The combat weight of the aircraft divided by the wing area.

Instantaneous Load Factor. The maximum instantaneous load factor the aircraft can achieve at an altitude of 25,000 ft and a Mach number of .8 at its combat weight.

Breguet Range Factor. The maximum value of the product of the average cruise speed and lift-to-drag ratio divided by the specific fuel consumption (the coefficient of the logarithmic term of the Breguet range equation).

Breguet Range. The range calculated using the Breguet range equation assuming all internal fuel is used under cruise conditions and the aircraft is initially loaded to its maximum gross weight.

Internal Fuel Fraction. The weight of usable fuel that can be carried internally divided by the quantity, the full internal weight minus the weight of the fuel carried internally. The latter quantity is sometimes referred to as the zero fuel weight.

Total Fuel Fraction. The total weight of usable fuel carried internally and externally divided by the weight of the aircraft with all tanks drained (internal and external).

Payload Fraction. The difference in the maximum gross weight and the full internal weight, all divided by the maximum gross weight of the aircraft.

Useful Load Fraction. The difference in the maximum gross weight and the empty weight, all divided by the maximum gross weight.

Range × Payload Fraction. The product of the payload fraction and the Breguet range.

Carrier Capability. Denotes whether aircraft can operate from carriers ("1" = no, "0" = yes).

Speed Class. This variable denotes whether the aircraft can sustain supersonic flight ("1" denotes subsonic aircraft, "0" denotes supersonic aircraft).

Design Class. This variable denotes whether the aircraft is classified as a new ("1") or derivative ("0") design.

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maximum velocity condition (e.g., structural limitations). Using static thrust instead of actual thrust also tends to understate specific power for earlier subsonic turbojets with afterburners, while it provides a fairly good approximation for Mach 2-class aircraft and subsonic aircraft without afterburners.

In the regression expressions, we computed specific power by expressing thrust in pounds, velocity in knots, and weight in pounds, absorbing the conversion factor in the regression coefficient.

Mission. **This variable denotes whether an aircraft's primary mission is air-to-air ("0") or air-to-ground ("1").**

Variable Geometry. **This variable denotes whether the aircraft has a variable geometry wing ("1" denotes a swing wing, "0" denotes a fixed wing).**

Design Lag. **The number of months between the first flight date and the early first flight date.**

Design Antecedent. **This variable denotes whether the aircraft had a hardware antecedent ("0" = yes, "1" = no).**

Appendix B
WORKING DEFINITIONS OF AIRCRAFT PARAMETERS

Appendix A provides formal definitions and absolute values of the aircraft parameters expressed in appropriate engineering units. To avoid possible computer rounding errors in the statistical analysis and to obtain interpretable computer output, we scaled some of the parameters. Table B.1 illustrates the scaling and the shorthand notation for those parameters, as well as the notation for unscaled parameters.

Table B.1

WORKING DEFINITIONS OF AIRCRAFT PARAMETERS

Parameter	Working Definition	Notation
Scaled		
Maximum velocity	Maximum velocity/100	VMX
Maximum climb rate	Maximum climb rate/10000	RCL
Maximum specific energy	Maximum specific energy/10000	ENS
Combat ceiling	Combat ceiling/10000	CLG
Sustained load factor	Sustained load factor/10	SLF
Specific power[a]	Thrust × Maximum velocity/ (100 × Combat weight)	SPR
Breguet range factor	Breguet range factor/10000	RGF
Breguet range	Breguet range/1000	RNG
Payload fraction × Breguet range	Payload fraction × Breguet range/1000	PFR
Empty weight	Empty weight/10000	EWT
Unscaled[b]		
Maximum gross weight	—	WTG
Full fuel weight	—	WTF
Full internal weight	—	WTI
Combat weight	—	CWT
Zero fuel weight	—	WTZ
Structure weight	—	SWT
Stress design weight	—	SDW
Internal fuel weight	—	WFI
External fuel weight	—	WTX
Design load factor	—	DLF
Structural efficiency	—	SEF
Internal fuel fraction	—	FFR
Total fuel fraction	—	TFF
Payload fraction	—	PLF
Useful load fraction	—	ULF
Thrust-to-weight ratio	—	TWR
Wing loading	—	WLG
Carrier capability	—	CAR
Variable geometry	—	VGY
Speed class	—	SPD
Mission	—	ATG
Design class	—	NEW
First flight date	—	FFT
Early first flight date	—	EFT
Design lag	—	LAG
Design antecedent	—	ANT

[a]Thrust expressed in pounds, velocity in knots, weight in pounds. The factor to convert specific power to appropriate units (hp/lb) is absorbed in the regression coefficients.

[b]Used exactly as defined in Appendix A either directly or in the computation of other parameter values.

Appendix C

TIME INTERVALS BETWEEN FIRST FLIGHT DATES OF U.S. AIRCRAFT

Table C.1 and Fig. C.1 illustrate the time interval between first flight of experimental or prototype U.S. aircraft and subsequent developmental aircraft. The full 25 aircraft sample has a mean interval of 23 months and a median interval of 21 months.

Three programs did not use vehicles classified as experimental or prototype hardware (F11F-1, F-14A, and F-15A), while the XF10F-1 and YF-107A programs did not proceed into full-scale development. If we exclude these five programs, the mean time interval for those aircraft having hardware antecedents becomes 28 months and the median interval becomes 23 months.

Table C.1

AIRCRAFT DESIGN ANTECEDENTS

Aircraft	First Flight Date[a]	Hardware Antecedent	First Flight Date[a]	Design Lag (months)
FH-1	82	XFH-1	61	21
FJ-1	89	XFJ-1	83	6
F-86A	101	XP-86	94	7
F9F-2	107	XF9F-2	95	12
F-94A	115	XP-80	49	66
F3D-1	122	XF3D-1	99	23
F-89A	127	XF-89	104	23
XF10F-1	137	None	—	0
F9F-6	147	XF9F-2	95	52
F-100A	166	YF-100A	161	5
F4D-1	174	XF4D-1	133	41
F11F-1	175	None	—	0
F-101A	177	XF-88	106	71
F3H-2	184	XF3H-1	140	44
F-102A	187	YF-102	166	21
F-8A	189	F8U-1 (prot.)	183	6
F-104A	194	XF-104	170	24
F-105B	197	YF-105A	190	7
YF-107A	201	None	—	0
F-106A	204	YF-102	166	38
F-4B	255	F4H-1	221	34
F-111A	328	F-111A (pre-prod.)	300	28
F-14A	372	None	—	0
F-15A	392	None	—	0
F-16A	444	YF-16	410	34

[a]Measured in months since January 1, 1940.

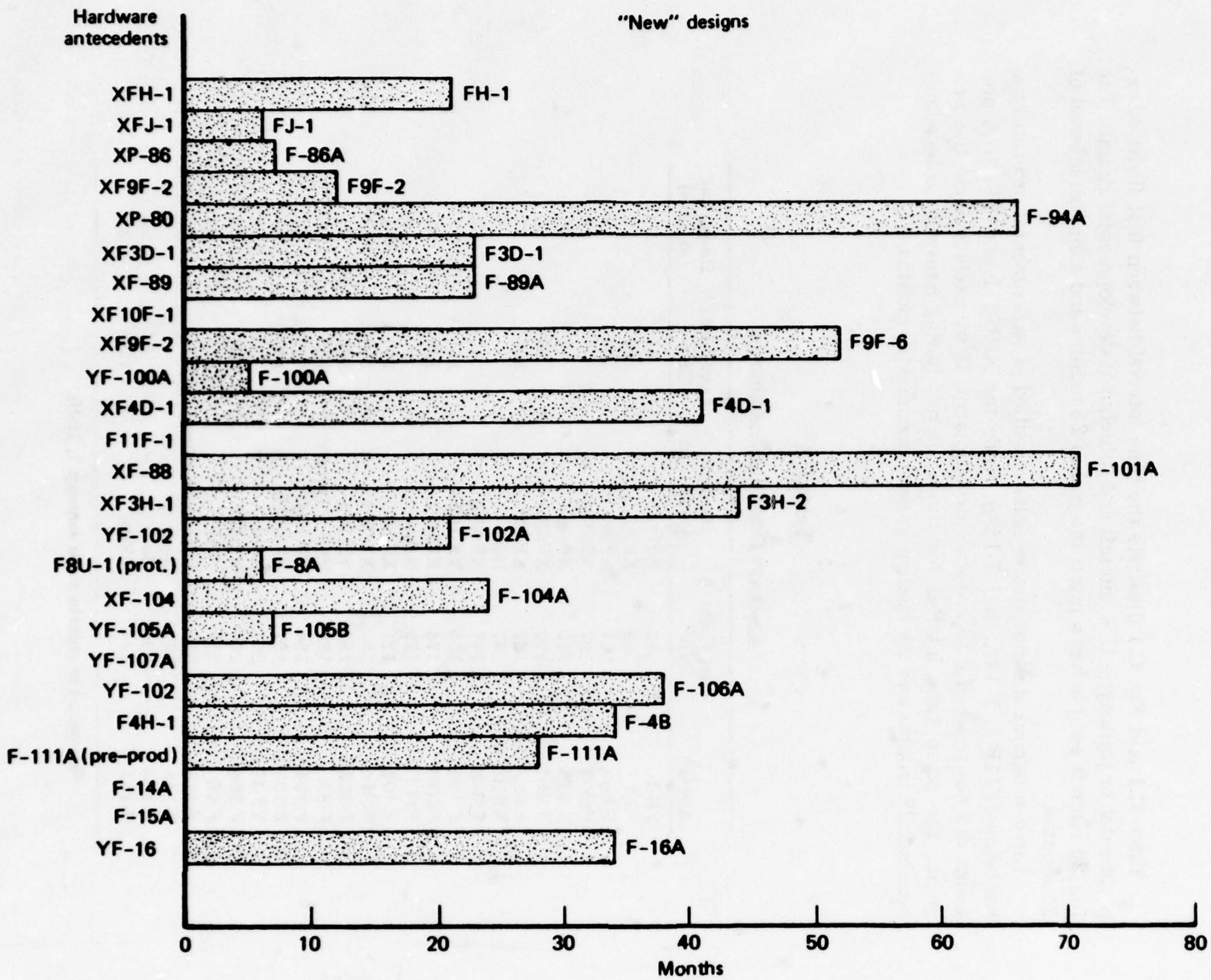


Fig. C.1—Time intervals between flight of new designs and hardware antecedents

Appendix D

STATISTICAL PROPERTIES OF TECHNOLOGY EQUATIONS

This appendix includes a summary of some of the key statistical properties of the various U.S. and Soviet technology expressions evaluated in the analysis, a correlation matrix for the independent and dependent variables used in the analysis, residual scatterplots used as an aid in evaluating the selection of an appropriate time origin, residual scatterplots used as an aid in evaluating the most desirable equation form, graphical plots of the residuals from some of the technology equations to test whether they appear normally distributed, the results of a technology equation stability check, and some graphical representations of U.S. technology Eqs. (2) and (3).

SUMMARY STATISTICS FOR REGRESSION EQUATIONS

Table D.1 summarizes some of the key statistical properties of the various regression equations evaluated in the analysis. Each equation had as its dependent variable "First Flight Date" (denoted by FFT), measured in months since January 1, 1940.[1] Each equation included from three to nine independent variables.[2] We evaluated four equation forms:[3]

Linear-Linear

$$FFT = b_0 + b_1x_1 + b_2x_2 + \ldots + b_kx_k .$$

Linear-Log

$$FFT = b_0 + b_1\ln(x_1) + b_2\ln(x_2) + \ldots + b_k\ln(x_k) .$$

Log-Linear

$$\ln(FFT) = b_0 + b_1x_1 + b_2x_2 + \ldots + b_kx_k .$$

Log-Log

$$\ln(FFT) = b_0 + b_1\ln(x_1) + b_2\ln(x_2) + \ldots + b_k\ln(x_k) .$$

The numbers appearing in the "Constant Term" column in the table represent b_0, and those appearing under "Regression Equation Coefficients" represent b_1, $b_2, \ldots, b_k$. Thus, for example, the first line of the table represents the equation:

$$\ln(FFT) = 4.111 + .101\ SPR + .370\ RNG + .558\ PLF.$$

[1] In Table D.1 we have included statistical results for equations having origins of 1900, 1920, 1930, 1942, and 1945. We used these parametric excursions to determine an appropriate origin selection.

[2] Appendix B explains shorthand notation and scaling for the independent variables, and Appendix A contains a complete definition for each variable.

[3] Logarithmic forms use natural logarithms.

Table D.1

Summary Statistics for Technology Equations

Independent Variables	Equation Form	Number of Cases	Regression Equation Coefficients	Constant Term	R^2	SEE[a]	Significance of Coefficients[b]	F Stat.	Durbin Watson Stat.	Key Residuals (months) F-4B	F-111A	F-14A	F-15A	F-16A
Sample of New U.S. Fighter Designs														
SPR RNG PLF	Log-Lin	25	.101 .370 .558	4.111	.888	.160	E-6 .001 .500	55.5	1.66	2	-8	53	-83	96
SPR RNG PLF CAR	Log-Lin	25	.105 .368 .552 -.057	4.126	.892	.161	E-6 .001 .500 .500	41.2	1.64	-8	1	39	-85	99
SPR RNG SLF PLF	Log-Lin	25	.062 .406 1.315 .923	3.871	.936	.124	.001 E-4 .001 .050	73.2	1.89	21	14	58	-46	52
SPR RNG SLF PLF CAR	Log-Lin	25	.065 .406 1.409 .939 -.093	3.878	.945	.117	.001 E-5 .001 .020 .100	65.8	1.92	5	28	36	-47	54
SPR RNG SLF PLF CAR LAG	Log-Lin	25	.067 .406 1.398 .847 -.103 .001	3.857	.950	.116	E-4 E-5 .001 .050 .100 .500	56.5	2.07	-2	26	42	-37	49
SPR RNG SLF PLF CAR ANT	Log-Lin	25	.068 .412 1.416 .895 -.105 -.052	3.879	.947	.118	.001 E-4 .001 .050 .100 .500	53.8	1.96	-1	23	43	-37	47
SPR RNG SLF PLF CAR SEF	Log-Lin	24	.067 .409 1.368 .989 -.081 3.559	3.730	.947	.122	.001 E-4 .001 .050 .200 .500	50.9	2.05	10	25	27	-53	65
SPR RNG SLF PLF CAR LAG VGY SPD ATG	Log-Lin	25	.062 .271 1.455 .620 -.121 .002 .158 -.099 .047	4.086	.958	.115	.002 .050 .001 .200 .100 .200 .200 .500 .800	38.3	1.84	-7	18	16	-5	65
SPR RGP FFR SLF	Log-Lin	25	.069 1.012 1.003 1.153	3.677	.927	.132	E-4 .050 .002 .010	63.7	1.98	16	34	58	-56	56
SPR RGP FFR SLF CAR	Log-Lin	25	.072 1.257 .876 1.184 -.105	3.643	.938	.125	E-4 .010 .005 .005 .100	57.2	1.91	5	46	21	-53	64
SPR RGP FFR SLF CAR LAG	Log-Lin	25	.072 1.673 .718 1.115 -.147 .003	3.482	.949	.116	E-5 .002 .020 .005 .050 .100	56.1	1.89	0	40	9	-26	56

[a]Expressed in logarithmic or absolute terms (months), depending on the equation form.

[b]These numbers represent upper bounds for the risk involved in incorrectly rejecting the hypothesis that the corresponding regression coefficient is 0. The notation E-n denotes powers of 10 (e.g. E-5 represents .00001). A blank entry (denoted by --) means that the corresponding independent variable did not enter into the regression equation.

Table D.1-continued

Independent Variables	Equation Form	Number of Cases	Regression Equation Coefficients	Constant Term	R^2	SEE	Significance of Coefficients	F Stat.	Durbin Watson Stat.	Key Residuals (months) F-4B	F-111A	F-14A	F-15A	F-16A
Sample of New U.S. Fighter Designs														
SPR RGF FFR SLF CAR LAG VGY ATG SPD	Log-Lin	25	.068 .905 .544 1.332 -.146 .003 .155 .091 -.080	3.879	.957	.116	.001 .200 .100 .002 .050 .050 .200 .500 .500	37.5	1.81	-8	25	6	-3	70
SPR RGF SLF CAR TFF	Log-Lin	25	.059 1.768 1.186 -.168 .526	3.530	.922	.140	.005 .001 .010 .020 .050	45.2	1.44	11	61	17	-40	42
SPR RGF SLF CAR LAG TFF VGY SPD ATG	Log-Lin	25	.058 1.181 1.323 -.186 .004 .301 .176 -.111 .076	3.855	.952	.124	.005 .200 .005 .020 .050 .500 .200 .500 .500	32.8	1.70	-7	33	0	13	59
SPR RGF SLF CAR ULF	Log-Lin	25	.068 1.742 1.177 -.138 .824	3.413	.911	.150	.002 .002 .020 .100 .200	38.8	1.31	15	83	-11	-48	53
SPR RGF SLF CAR LAG ATG VGY SPD ULF	Log-Lin	25	.062 .858 1.401 -.164 .003 .107 .228 -.133 .444	3.930	.949	.128	.005 .500 .005 .050 .050 .500 .100 .200 .500	30.7	1.73	-7	41	-15	14	70
RCL RNG SLF PLF CAR	Log-Lin	25	.093 .500 1.585 1.282 -.099	3.763	.927	.136	.005 E-5 .001 .005 .200	48.1	1.68	18	47	26	18	44
ENS SLF RNG PLF CAR	Log-Lin	24	.055 2.031 .360 1.171 -.106	3.632	.921	.143	.010 E-5 .002 .050 .200	41.9	1.67	8	3	23	-5	100
VMX TWR RNG EWT PLF CAR WLG CLG	Log-Lin	25	.023 1.420 .418 .089 .771 -.068 -.002 --	3.546	.940	.130	.500 E-4 .005 .200 .200 .500 .500 --	37.8	2.49	-4	-11	39	-75	89
SPR RNG CAR SLF PLF	Log-Log[a]	25	.536 .271 -.133 .042 .009	4.517	.885	.170	E-5 .050 .500 .500 .800	29.2	1.15	-27	61	48	39	139
SPR RNG SPD CAR VGY SLF LAG PLF ATG	Log-Log	25	.613 .268 .175 -.104 .184 .037 .007 .008 --	4.308	.899	.174	.001 .100 .500 .500 .500 .800 .800 .800 --	17.8	1.37	-24	29	27	43	132

[a] To avoid undefined logarithmic terms in the log-log and linear-log equation forms, all dummy independent variables (viz. CAR, SPD, NEW, ATG, VGY, LAG, ANT) should be replaced by themselves plus 1 in the relevant equations. Thus, for example, this particular line of the table represents the equation:

$$\ln(FFT) = 4.517 + .536 * \ln(SPR) + .271 * \ln(RNG) - .133 * \ln(1 + CAR) + .042 * \ln(SLF) + .009 * \ln(PLF)$$

Table D.1-continued

Independent Variables	Equation Form	Number of Cases	Regression Equation Coefficients	Constant Term	R^2	SEE	Significance of Coefficients	F Stat.	Durbin Watson Stat.	F-4B	F-111A	F-14A	F-15A	F-16A
Sample of New U.S. Fighter Designs														
SPR FFR RGP CAR SLF	Log-Log	25	.501 .267 .452 -.156 .036	5.196	.899	.159	E-5 .050 .200 .200 .500	33.8	1.17	-21	42	36	41	127
SPR FFR VGY SLF CAR RGP SPD LAG ATG	Log-Log	25	.573 .283 .111 .026 -.118 .491 .165 .005 -.070	5.048	.909	.170	.001 .100 .800 .800 .500 .500 .500 .800 .800	16.6	1.45	-19	27	21	36	114
SPR RGP CAR TFF SLF	Log-Log	25	.438 .627 -.237 .277 .058	5.379	.893	.164	E-4 .050 .050 .100 .500	31.6	1.08	-18	51	40	41	113
SPR VGY SLF TFF CAR RGP ATG LAG SPD	Log-Log	25	.467 .172 .056 .281 -.197 .591 -.112 .007 .044	5.266	.901	.177	.005 .500 .500 .200 .200 .500 .800 .800 1.0	15.2	1.40	-20	36	23	40	102
SPR VGY SLF ULF CAR RGP LAG ATG SPD	Log-Log	25	.493 .243 .060 .311 -.158 .422 .006 -.056 --	5.178	.891	.180	E-4 .500 .500 .500 .500 .500 .800 .800 --	16.4	1.34	-17	44	-1	56	119
SPR RNG PLF SLF CAR	Lin-Lin	25	17.0 78.2 236.3 184.5 -21.5	-63.4	.895	34.7	.001 .001 .050 .100 .200	32.5	1.31	-24	21	41	-6	83
SPR RNG PLF SLF ATG VGY CAR SPD LAG	Lin-Lin	25	17.8 78.1 241.8 188.3 -23.9 27.4 -10.0 13.9 --	-81.9	.909	35.2	.005 .050 .100 .100 .500 .500 .800 .800 --	20.0	1.71	-15	18	23	-14	77
SPR RGP FFR CAR SLF	Lin-Lin	25	19.3 276.1 141.8 -25.9 118.5	-102.6	.888	35.8	E-4 .050 .100 .200 .500	30.2	1.32	-22	35	24	-9	96
SPR RGP FFR CAR SLF LAG	Lin-Lin	25	19.4 338.0 118.3 -32.0 108.3 0.4	-126.6	.894	35.9	E-4 .050 .200 .100 .500 .500	25.3	1.20	-25	32	19	0	93
SPR VGY SLF FFR SPD RGP CAR LAG ATG	Lin-Lin	25	21.4 19.9 128.5 128.5 26.4 316.2 -21.8 0.3 -5.5	-151.6	.906	37.0	.001 .800 .500 .200 .500 .200 .500 .500 1.0	16.1	1.62	-15	25	10	-14	88
SPR RGP CAR TFF SLF	Lin-Lin	25	16.1 358.6 -36.7 115.0 131.7	-135.1	.889	35.7	.002 .010 .050 .100 .500	30.4	1.25	-19	37	28	-2	81
SPR VGY SLF TFF CAR RGP LAG SPD ATG	Lin-Lin	25	17.6 19.9 131.0 113.5 -31.4 412.5 0.4 19.7 -17.2	-187.1	.909	36.5	.005 .800 .500 .200 .200 .100 .500 .500 .800	16.5	1.68	-14	28	13	-3	71
SPR VGY SLF ULF RGP CAR LAG SPD ATG	Lin-Lin	25	18.1 41.3 172.1 212.5 280.6 -20.5 0.3 9.7 -8.1	-172.7	.902	37.7	.005 .500 .200 .500 .500 .500 .800 .800 .800	15.4	1.55	-13	37	-1	-1	78

Table D.1-continued

Independent Variables	Equation Form	Number of Cases	Regression Equation Coefficients	Constant Term	R^2	SEE	Significance of Coefficients	F Stat.	Durbin Watson Stat.	F-4B	F-111A	F-14A	F-15A	F-16A
Sample of New U.S. Fighter Designs														
SPR RNG CAR SLF PLF	Lin-Log	25	121.2 55.7 -21.5 -7.7 2.4	16.8	.763	52.2	.001 .200 .800 .800 .800	12.2	0.71	-36	41	54	52	138
SPR VGY RNG SPD SLF ATG PLF CAR	Lin-Log	25	158.6 41.0 74.1 92.4 -13.8 -35.2 3.3 6.2	-85.0	.809	51.1	.001 .500 .200 .200 .500 .800 .800 1.0	8.5	1.34	-24	25	31	27	123
SPR PPR RGF CAR SLF	Lin-Log	25	111.0 54.1 125.1 -29.8 -10.6	181.8	.790	49.2	.001 .200 .200 .500 .500	14.3	0.72	-26	20	38	55	131
SPR VGY PPR SPD RGF SLF ATG CAR LAG	Lin-Log	25	149.8 2.2 76.6 100.9 197.4 -20.5 -57.2 -7.0 --	154.4	.838	47.0	.001 1.0 .100 .200 .200 .200 .500 1.0 --	10.4	1.40	-14	23	19	22	105
SPR TFF RGF CAR SLF	Lin-Log	25	93.9 72.7 160.7 -46.1 -5.1	236.8	.795	48.5	.002 .200 .100 .200 .800	14.8	0.72	-26	20	46	55	117
SPR VGY TFF ATG RGF SPD SLF CAR LAG	Lin-Log	25	116.4 14.0 92.0 -74.9 230.5 68.8 -12.1 -26.7 --	235.4	.838	47.1	.005 1.0 .100 .200 .100 .500 .500 .500 --	10.3	1.41	-14	30	24	26	91
SPR VGY ULF ATG RGF SPD SLF CAR LAG	Lin-Log	25	118.8 39.1 132.7 -62.1 170.6 47.3 -9.6 -9.5 -0.6	239.3	.823	50.7	.010 .800 .200 .500 .500 .500 .800 1.0 1.0	7.8	1.31	-11	37	4	33	103
Sample of New U.S. Fighter Designs (1900 Origin)														
SPR RNG PLF SLF CAR	Log-Lin	25	.023 .113 .312 .291 -.030	6.140	.920	.042	.001 .001 .050 .050 .200	43.5	1.54	-15	24	42	-14	80
Sample of New U.S. Fighter Designs (1920 Origin)														
SPR RNG SLF PLF CAR	Log-Lin	25	.034 .174 .477 .461 -.045	5.492	.929	.060	E-4 E-4 .010 .050 .200	50.0	1.67	-10	26	42	-20	77
Sample of New U.S. Fighter Designs (1930 Origin)														
SPR RNG SLF PLF CAR	Log-Lin	25	.045 .241 .708 .611 -.060	4.939	.937	.077	E-4 E-4 .005 .020 .100	56.8	1.80	-6	27	41	-27	72
Sample of New U.S. Fighter Designs (1942 Origin)														
SPR RNG SLF PLF CAR	Log-Lin	25	.070 .478 1.777 1.072 -.104	3.488	.945	.137	.001 E-5 .001 .020 .100	64.8	1.86	10	27	33	-56	42
Sample of New U.S. Fighter Designs (1945 Origin)														
SPR RNG SLF PLF CAR	Log-Lin	25	.075 .688 3.040 1.476 -.125	2.492	.930	.215	.010 E-4 E-4 .050 .200	50.6	1.53	24	21	23	-82	-3

Key Residuals (months): columns F-4B through F-16A.

Table D.1-continued

Independent Variables	Equation Form	Number of Cases	Regression Equation Coefficients			Constant Term	R^2	SEE	Significance of Coefficients			F Stat.	Durbin Watson Stat.	Key Residuals (months) F-4B	F-111A	F-14A	F-15A	F-16A
Sample of New U.S. Navy Fighter Designs																		
SPR SLF RNG PLF	Log-Lin	12	.081 .328	1.493	.299	4.029	.977	.083	.001 .800	.002	.020	73.1	3.07	-9	--	27	--	--
Sample of New U.S. Air Force Fighter Designs																		
SPR RNG PLF SLF	Log-Lin	13	.059 1.245	.426	1.153	3.803	.923	.151	.050 .200	.005	.100	24.1	2.23	--	15	--	-23	64
Sample of New U.S. Supersonic Fighter Designs																		
SPR RNG SLF PLF CAR	Log-Lin	14	.028 1.507	.525 -.134	2.672	3.512	.964	.083	.100 .005	E-4 .050	.002	42.3	2.10	17	19	20	-18	-1
Sample of New U.S. Subsonic Fighter Designs																		
SLF CAR SPR RNG PLF	Log-Lin	11	.082 .446	-.008 .289	.236	3.748	.848	.141	1.0 .200	1.0 .800	.200	5.6	1.61	--	--	--	--	--
Sample of 17 New U.S. Fighter Designs Through F-104A																		
SLF SPR RNG CAR PLF	Log-Lin	17	1.366 -.095	.071 .202	.224	4.180	.871	.122	.005 .500	.020 .800	.200	14.9	1.49	--	--	--	--	--
SLF SPR RNG CAR PLF	Lin-Lin	17	164.5 -15.2	11.5 --	24.1	52.1	.880	15.2	.005 .200	.002 --	.100	21.9	1.52	--	--	--	--	--
SPR SLF CAR RNG PLF	Log-Log	17	.362 .122	.097 -.002	-.177	4.778	.889	.113	.001 .500	.050 1.0	.100	17.6	1.46	--	--	--	--	--
SPR RNG CAR SLF PLF	Lin-Log	17	55.0 9.4	18.2 --	-24.0	109.9	.882	15.1	.001 .100	.200 --	.100	22.4	1.42	--	--	--	--	--
Sample of New U.S. Fighter Designs (Weighted)																		
SPR RNG SLF PLF CAR	Log-Lin	25	.045 1.452	.495 -.120	1.903	3.675	.967	.100					1.96	8	5	23	-29	23
SPR RGF FFR SLF CAR	Log-Lin	25	.054 1.685	1.500 -.104	1.161	3.395	.958	.115	(Not available)				2.01	11	19	8	-39	41
SPR RGF TFF SLF CAR	Log-Lin	25	.041 1.386	2.212 -.199	.803	3.234	.961	.110					1.67	14	24	6	-17	16

Table D.1-continued

Independent Variables	Equation Form	Number of Cases	Regression Equation Coefficients	Constant Term	R^2	SEE	Significance of Coefficients	F Stat.	Durbin Watson Stat.	Key Residuals (months) F-4B	F-111A	F-14A	F-15A	F-16A
Sample of Derivative U.S. Fighter Designs														
SPR PLF RNG CAB SLF	Log-Lin	14	.105 1.992 .298 -.025 --	4.057	.817	.161	.005 .020 .200 1.0 --	10.1	1.78	--	--	--	--	--
Sample of All U.S. Fighter Designs (New and Derivative)														
SPR SLF RNG PLF CAB	Log-Lin	39	.070 1.190 .350 1.417 -.062	3.899	.866	.157	E-5 .002 E-4 .001 .500	42.5	1.71	-5	32	44	-82	18
SPR SLF RNG PLF NEW CAR	Log-Lin	39	.077 1.064 .344 1.346 -.081 -.072	3.976	.874	.155	E-5 .005 E-4 .001 .200 .500	36.9	1.65	-5	39	45	-87	28
SPR SLF FFR RGF CAR	Log-Lin	39	.082 1.178 .729 .542 -.045	3.983	.825	.179	E-6 .010 .020 .200 .500	31.1	1.35	-11	72	53	-103	41
SPR SLF FFR RGF NEW CAR	Log-Lin	39	.091 .971 .667 .634 -.102 -.059	4.050	.838	.176	E-6 .050 .050 .200 .200 .500	27.5	1.36	-10	76	50	-109	52
SPR SLF TFF RGF CAR	Log-Lin	39	.070 1.140 .700 .662 -.091	3.899	.827	.179	.001 .010 .020 .100 .200	31.5	1.42	-16	75	80	-94	1
SPR SLF TFF RGF CAR NEW	Log-Lin	39	.080 .942 .634 .740 -.101 -.098	3.974	.838	.175	E-4 .050 .050 .100 .200 .200	27.6	1.37	-14	79	74	-100	16
Sample of New Soviet Fighter Designs														
SPR RNG SLF PLF	Log-Lin	13	.100 .497 .818 .458	3.733	.950	.122	E-4 .001 .500 .800	38.3	2.05					
SPR RNG PLF SLF	Log-Log	13	.575 .540 .098 .015	4.475	.958	.112	E-4 .001 .500 1.0	45.9	2.73					
SPR RNG PLF SLF	Lin-Log	13	90.7 124.4 46.8 11.9	164.9	.926	29.9	.005 .002 .100 1.0	25.2	1.40					
SPR RNG PLF SLF	Lin-Lin	13	17.5 105.2 286.7 133.9	-99.9	.973	18.0	E-4 E-4 .050 .500	72.8	2.08					
SPR RNG PLF	Lin-Lin	13	17.9 104.6 301.3	-57.8	.970	18.1	E-5 E-4 .020	95.9	2.21					
SPR RGF FFR	Lin-Lin	13	18.8 373.9 186.0	-129.2	.967	18.7	E-5 E-4 .005	89.2	2.71					
SPR RGF TFF	Lin-Lin	13	18.8 328.6 132.3	-107.3	.942	25.0	.001 .001 .050	49.0	2.18					

By substituting the three parameter values for a particular aircraft and exponentiating, we obtain a prediction for the first flight date of that aircraft.

The coefficient of determination (R^2) measures the proportion of the total variation about the mean value of the dependent variable explained by the combined linear influence of the independent variables. If y_i denotes the actual ith observation of the dependent variable, and $\hat{y}_i$ denotes the corresponding predicted value, then

$$R^2 = \frac{\sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} ,$$

where $\bar{y}$ is the sample mean of the y_i and n is the number of sample points.

The standard error of estimate (SEE) is the standard deviation of the actual y_i values from the predicted $\hat{y}_i$ values. If k is the number of independent variables, the standard error of estimate is given by

$$SEE = \left(\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{n-k-1} \right)^{1/2}$$

We used R^2 and SEE to evaluate the accuracy with which the various regression equations fitted the observations.

We used t-values (that is, $b_i/\hat{\sigma}_i$, the ratio of a regression coefficient to its standard error) to test the hypothesis that a given regression coefficient is zero. The numbers under "Significance of Coefficients" represent upper bounds for the risk involved in incorrectly rejecting the hypothesis that the corresponding coefficient is zero. In general, the smaller this bound, the less likely the coefficient is actually zero.

We used the F-statistic, defined as

$$F = \frac{R^2/k}{(1 - R^2)/(n - k - 1)} ,$$

to collectively test the hypothesis that *all* the regression coefficients equal zero simultaneously. The greater the value of the F-statistic, the greater the evidence that some of the coefficients are nonzero.

The Durbin-Watson statistic was used to test for correlation among the residuals in our sequenced (by first flight date) data set. This statistic, d, is given by

$$d = \frac{\sum_{i=2}^{n} (e_i - e_{i-1})^2}{\sum_{i=1}^{n} e_i^2},$$

where $e_i = y_i - \hat{y}_i$ is the residual corresponding to the ith sample observation. The number d is always between 0 and 4, and the closer it is to 2 the less serial correlation there is between the residuals. A d value significantly different from 2 suggests that an ordinary least squares regression fit might not be appropriate.

The last five columns of the table show the residuals for the five most recent fighter designs in the U.S. sample. A positive residual suggests an aircraft flew later than the trend predicts, and a negative residual suggests the opposite.

CORRELATION AMONG THE INDEPENDENT VARIABLES

Given two variables X and Y, we can ask how variation (or change) in one is related to variation in the other. If Y tends to increase as X increases, we say that X and Y are positively correlated. If Y tends to decrease as X increases, they are negatively correlated. If there is no relationship indicated, they are called uncorrelated. If x_i and y_i are the ith observations of X and Y, then the quotient

$$r = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\left\{\left[\sum_{i=1}^{n} (x_i - \bar{x})^2\right]\left[\sum_{i=1}^{n} (y_i - \bar{y})^2\right]\right\}^{1/2}}$$

is called the linear correlation coefficient of X and Y, where n is the number of observations and $\bar{x}$ and $\bar{y}$ are the sample means of the two variables. This coefficient measures the degree to which the observations x_i and y_i satisfy a linear relationship (lie on a straight line). An r value near +1 indicates a positive linear correlation, one near -1 a negative linear correlation, and one near 0 a lack of linear correlation.

In Table D.2, we present these linear correlation coefficients for each pair of independent variables used in the regression analyses presented in Sec. III for the sample of 25 new U.S. fighter designs, as well as correlations for the dependent flight date variables. The table shows the rather high positive correlation between the independent variables "specific power" and "sustained load factor." For the sake of completeness, we have also included Table D.3, which gives correlation coefficients for *all* pairs of variables, including those never used in the same regression equation.

Table D.2

CORRELATION MATRIX FOR U.S. AIRCRAFT PARAMETERS[a]

	FFT	EFT	LFT	EWT	SEF	VMX	SPR	ENS	RCL	CLG	SLF	TWR	WLG	RGF	RNG	FFR	TFF	PLF	ULF	PFR	CAR	SPD	ATG	VGT	LAG	ANT	
FFT	1.00	0.98	0.97	0.61	-0.21	0.82	0.89	0.77	0.79	0.76	0.72	0.81	0.50	0.70	0.50	0.42	0.63	0.31	0.44	0.70	0.26	-0.65	0.19	0.33	-0.08	0.33	FFT
EFT	-	1.00	0.94	0.60	-0.17	0.82	0.87	0.77	0.78	0.73	0.71	0.77	0.48	0.74	0.51	0.40	0.59	0.25	0.39	0.66	0.22	-0.67	0.22	0.37	-0.29	0.43	EFT
LFT[b]	-	-	1.00	0.68	-0.21	0.87	0.89	0.79	0.80	0.82	0.79	0.82	0.56	0.73	0.55	0.45	0.60	0.24	0.38	0.65	0.28	-0.74	0.24	0.31	-0.05	0.33	LFT
EWT	-	-	-	1.00	-	0.70	0.50	-	-	0.47	0.38	0.31	0.72	-	0.74	0.56	-	-0.08	-	0.48	0.25	-	-	-	-	-	EWT
SEF	-	-	-	-	1.00	-	-0.25	-	-	-	-0.16	-	-	-	-0.21	-	-	0.04	-	-	-0.11	-	-	-	-	-	SEF
VMX	-	-	-	-	-	1.00	-	-	-	0.81	-	0.72	0.65	-	0.52	-	-	0.23	-	-	0.39	-	-	-	-	-	VMX
SPR	-	-	-	-	-	-	1.00	-	-	-	0.74	-	0.42	0.58	0.30	0.24	0.61	0.37	0.39	0.58	0.38	-0.74	0.15	0.10	-0.09	0.32	SPR
ENS	-	-	-	-	-	-	-	1.00	-	-	0.51	-	-	0.68	0.42	-	-	0.40	-	-	0.25	-	-	-	-	-	ENS
RCL	-	-	-	-	-	-	-	-	1.00	-	0.75	-	-	-	0.17	-	-	0.36	-	-	0.41	-	-	-	-	-	RCL
CLG	-	-	-	-	-	-	-	-	-	1.00	-	0.89	0.40	0.53	0.29	-	-	0.22	-	-	0.48	-	-	-	-	-	CLG
SLF	-	-	-	-	-	-	-	-	-	-	1.00	-	-	0.55	0.23	0.08	0.31	0.14	0.05	0.30	0.38	-0.60	0.03	-0.03	-0.06	0.25	SLF
TWR	-	-	-	-	-	-	-	-	-	-	-	1.00	0.22	-	0.09	-	-	0.41	-	-	0.36	-	-	-	-	-	TWR
WLG	-	-	-	-	-	-	-	-	-	-	-	-	1.00	-	0.72	-	-	0.12	-	-	0.27	-	-	-	-	-	WLG
RGF	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	-	0.35	0.33	0.05	0.16	-	0.43	-0.67	0.47	0.53	-0.31	0.36	RGF
RNG	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	-	-	-0.38	-	-	0.10	-0.48	0.41	0.59	-0.16	0.31	RNG
FFR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	-	-	-	-	-0.08	-0.29	0.29	0.43	0.06	0.15	FFR
TFF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	-	-	-	0.26	-0.44	0.39	0.19	0.07	-	TFF
PLF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	-	-	0.14	-0.04	0.17	-0.08	0.19	-0.11	PLF
ULF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	-	-0.05	-0.16	0.24	0.11	0.18	-	ULF
PFR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	0.19	-	-	-	-	-	PFR
CAR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	-0.44	0.35	-0.14	0.12	-0.12	CAR
SPD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	-0.33	-0.08	0.19	-	SPD
ATG	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	0.24	-0.20	-	ATG
VGT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	-0.24	-	VGT
LAG	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	-	LAG
ANT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	ANT

[a] Correlations are indicated only for pairs of variables that appear together in at least one regression equation.

[b] Logarithm of first flight date (FFT).

Table D.3

CORRELATION MATRIX FOR ALL U.S. AIRCRAFT PARAMETERS TESTED

	FFT	EFT	LFT	EWT	SEF	VMX	SPR	EWS	RCL	CLG	SLF	TWR	WLG
FFT	1.00	0.98	0.97	0.61	-0.21	0.82	0.89	0.77	0.79	0.76	0.72	0.81	0.50
EFT	-	1.00	0.94	0.60	-0.17	0.82	0.87	0.77	0.78	0.73	0.71	0.77	0.48
LFT[a]	-	-	1.00	0.68	-0.21	0.87	0.89	0.79	0.80	0.82	0.79	0.82	0.56
EWT	-	-	-	1.00	0.09	0.70	0.50	0.57	0.38	0.47	0.38	0.31	0.72
SEF	-	-	-	-	1.00	-0.24	-0.25	-0.23	-0.18	-0.30	-0.16	-0.26	-0.10
VMX	-	-	-	-	-	1.00	0.90	0.91	0.85	0.81	0.64	0.72	0.65
SPR	-	-	-	-	-	-	1.00	0.86	0.95	0.87	0.74	0.92	0.42
EWS	-	-	-	-	-	-	-	1.00	0.77	0.72	0.51	0.70	0.57
RCL	-	-	-	-	-	-	-	-	1.00	0.83	0.75	0.89	0.35
CLG	-	-	-	-	-	-	-	-	-	1.00	0.80	0.89	0.40
SLF	-	-	-	-	-	-	-	-	-	-	1.00	0.81	0.19
TWR	-	-	-	-	-	-	-	-	-	-	-	1.00	0.22
WLG	-	-	-	-	-	-	-	-	-	-	-	-	1.00
RGF	-	-	-	-	-	-	-	-	-	-	-	-	-
RNG	-	-	-	-	-	-	-	-	-	-	-	-	-
FFR	-	-	-	-	-	-	-	-	-	-	-	-	-
TFF	-	-	-	-	-	-	-	-	-	-	-	-	-
PLF	-	-	-	-	-	-	-	-	-	-	-	-	-
ULF	-	-	-	-	-	-	-	-	-	-	-	-	-
PFR	-	-	-	-	-	-	-	-	-	-	-	-	-
CAR	-	-	-	-	-	-	-	-	-	-	-	-	-
SPD	-	-	-	-	-	-	-	-	-	-	-	-	-
ATG	-	-	-	-	-	-	-	-	-	-	-	-	-
VGY	-	-	-	-	-	-	-	-	-	-	-	-	-
LAG	-	-	-	-	-	-	-	-	-	-	-	-	-
ANT	-	-	-	-	-	-	-	-	-	-	-	-	-

	RGF	RNG	FFR	TFF	PLF	ULF	PFR	CAR	SPD	ATG	VGY	LAG	ANT	
FFT	0.70	0.50	0.42	0.63	0.31	0.44	0.70	0.26	-0.65	0.19	0.33	-0.08	0.33	FFT
EFT	0.74	0.51	0.40	0.59	0.25	0.39	0.66	0.22	-0.67	0.22	0.37	-0.29	0.43	EFT
LFT[a]	0.73	0.55	0.45	0.60	0.24	0.38	0.65	0.28	-0.74	0.24	0.31	-0.05	0.33	LFT
EWT	0.71	0.74	0.56	0.38	-0.08	0.10	0.48	0.25	-0.52	0.51	0.63	-0.06	0.28	EWT
SEF	-0.18	-0.21	-0.15	-0.17	0.04	-0.24	-0.01	-0.11	0.36	0.08	0.21	-0.16	0.29	SEF
VMX	0.75	0.52	0.37	0.59	0.23	0.35	0.59	0.39	-0.82	0.42	0.29	-0.14	0.30	VMX
SPR	0.58	0.30	0.24	0.61	0.37	0.39	0.58	0.38	-0.74	0.15	0.10	-0.09	0.32	SPR
EWS	0.68	0.42	0.33	0.63	0.40	0.48	0.70	0.25	-0.72	0.33	0.32	-0.13	0.33	EWS
RCL	0.52	0.17	0.10	0.54	0.36	0.32	0.47	0.41	-0.73	0.12	0.01	-0.13	0.34	RCL
CLG	0.53	0.29	0.17	0.50	0.22	0.19	0.42	0.48	-0.75	0.16	0.04	0.00	0.18	CLG
SLF	0.55	0.23	0.08	0.31	0.14	0.05	0.30	0.38	-0.60	0.03	-0.03	-0.06	0.25	SLF
TWR	0.41	0.09	0.07	0.49	0.41	0.33	0.47	0.36	-0.64	-0.03	-0.07	0.05	0.25	TWR
WLG	0.60	0.72	0.69	0.62	0.12	0.45	0.63	0.27	-0.59	0.62	0.52	-0.02	0.25	WLG
RGF	1.00	0.69	0.35	0.33	0.05	0.16	0.54	0.43	-0.67	0.47	0.53	-0.31	0.36	RGF
RNG	-	1.00	0.84	0.41	-0.38	0.12	0.40	0.10	-0.48	0.41	0.59	-0.16	0.31	RNG
FFR	-	-	1.00	0.66	-0.14	0.44	0.55	-0.08	-0.29	0.29	0.43	0.06	0.15	FFR
TFF	-	-	-	1.00	0.47	0.73	0.83	0.26	-0.44	0.39	0.19	0.07	0.08	TFF
PLF	-	-	-	-	1.00	0.77	0.66	0.14	-0.04	0.17	-0.08	0.19	-0.11	PLF
ULF	-	-	-	-	-	1.00	0.81	-0.05	-0.16	0.24	0.11	0.18	-0.06	ULF
PFR	-	-	-	-	-	-	1.00	0.19	-0.37	0.39	0.39	0.05	0.14	PFR
CAR	-	-	-	-	-	-	-	1.00	-0.44	0.35	-0.14	0.12	-0.12	CAR
SPD	-	-	-	-	-	-	-	-	1.00	-0.33	-0.08	0.19	-0.24	SPD
ATG	-	-	-	-	-	-	-	-	-	1.00	0.24	-0.20	0.12	ATG
VGY	-	-	-	-	-	-	-	-	-	-	1.00	-0.24	0.43	VGY
LAG	-	-	-	-	-	-	-	-	-	-	-	1.00	-0.55	LAG
ANT	-	-	-	-	-	-	-	-	-	-	-	-	1.00	ANT

[a]Logarithm of first flight date (FFT).

Table D.4 shows the corresponding correlation matrix for Soviet aircraft. There is evidence of a rather high positive correlation between specific power and payload-related variables such as payload fraction and fuel fraction.

Table D.4

CORRELATION MATRIX FOR SOVIET AIRCRAFT PARAMETERS[a]

	FFT	SPR	SLF	PLF	RNG	TFF	RGF	FFR
FFT	1.00	0.84	0.30	0.60	0.64	0.76	0.45	0.65
SPR	—	1.00	0.28	0.53	0.20	0.65	0.01	0.55
SLF	—	—	1.00	0.26	0.02	-0.04	0.07	0.01
PLF	—	—	—	1.00	0.13	—	—	—
RNG	—	—	—	—	1.00	—	—	—
TFF	—	—	—	—	—	1.00	0.15	—
RGF	—	—	—	—	—	—	1.00	-0.05
FFR	—	—	—	—	—	—	—	1.00

[a]Correlations are indicated only for pairs of variables that appear together in at least one regression equation.

RESIDUAL PATTERNS FOR EQUATIONS USING DIFFERENT ORIGINS

We plotted the residuals (observed minus calculated first flight date) versus the calculated first flight date for equations having origins of January 1, 1900, 1920, 1930, 1940, 1942, and 1945 (see Figs. D.1, D.2, and D.3). We ultimately used January 1, 1940 as the time origin for all computations.

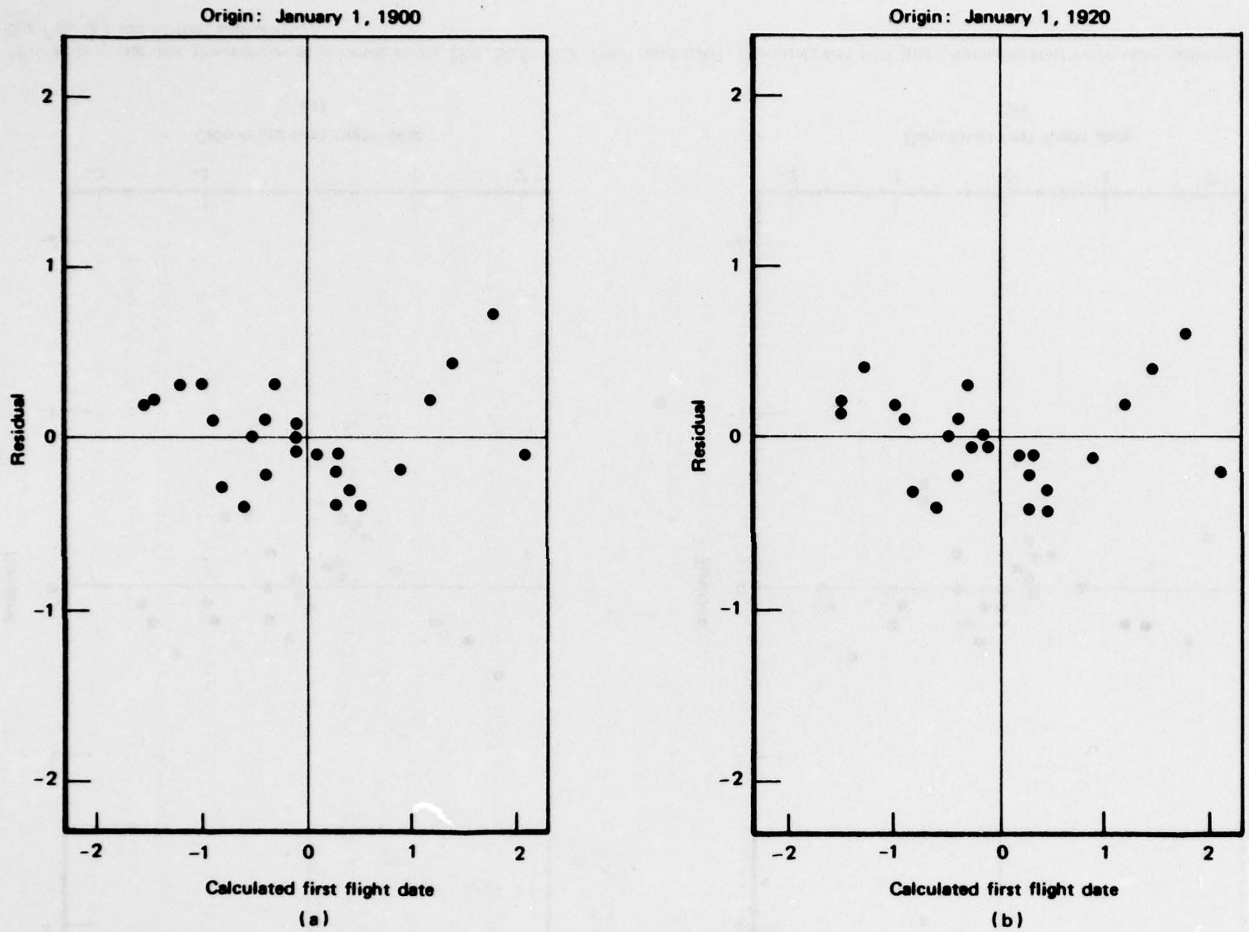
RESIDUAL PATTERNS FOR VARIOUS EQUATION FORMS

We plotted the residuals (observed minus calculated first flight date) versus the calculated first flight date for the four equation forms tested, as one criterion for determining the most desirable equation form (see Figs. D.4 and D.5). The log-linear equation form exhibited the most satisfying residual patterns for U.S. aircraft.

NORMALITY OF RESIDUAL DISTRIBUTIONS FOR U.S. EQUATIONS

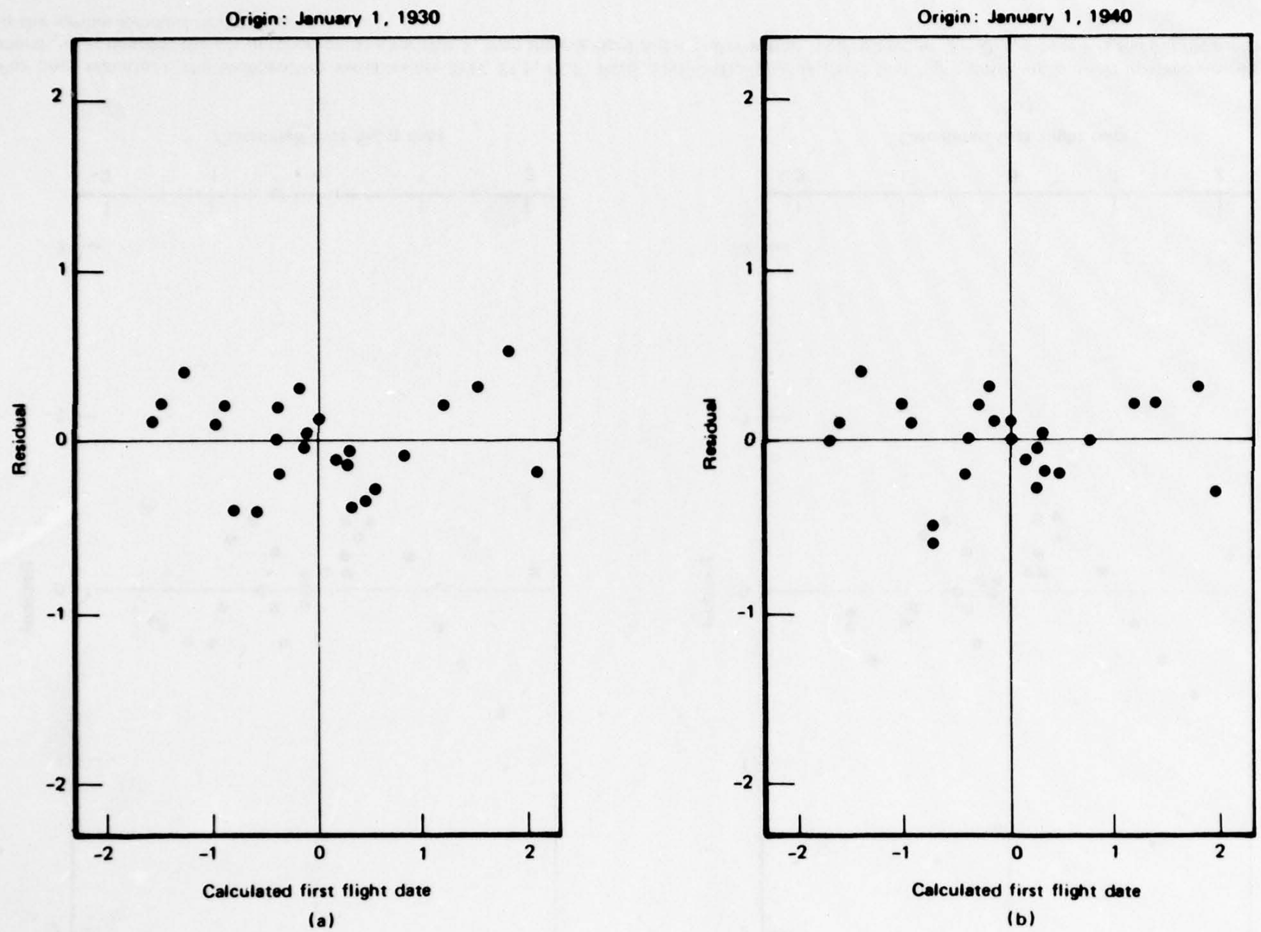
We made some simple plots on normal probability paper of residual distributions for Eqs. 1, 2, and 3 to visually test whether the residuals seemed normally distributed. We first arranged the standardized residuals (see Fig. D.1 for explanation) $e_1, e_2, e_3, \ldots, e_{25}$ in increasing order of magnitude $e_{(1)} \leq e_{(2)} \leq \ldots \leq e_{(25)}$, and then plotted each value $e_{(i)}$ against the percentage point $\dfrac{100(i - .5)}{25}$.

If the residuals e_i are approximately normally distributed, the graph should be roughly a straight line. The results shown in Fig. D.6 generally suggest that the



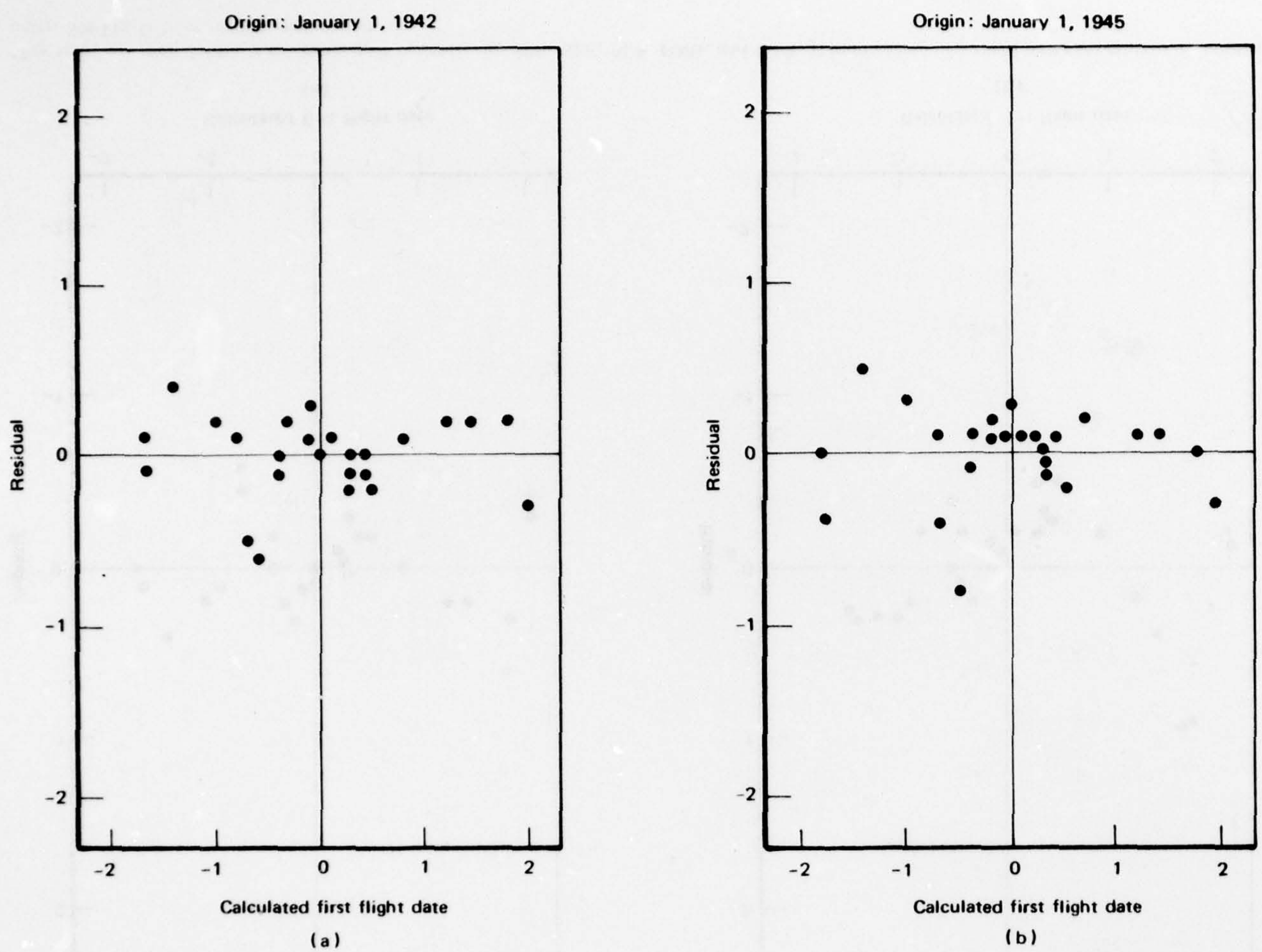
*For both equations, the independent variables are SPR, SLF, PLF, RNG, and CAR. Residuals and first flight dates are plotted in standardized units. In general, if x_i denotes the ith observation of a variable x, then the standardized ith observation is calculated as $(x_i - \overline{x})/\sigma$, where $\overline{x}$ is the sample mean of x and σ is the sample standard deviation of x.

Fig. D.1—Residual scatterplots for equations having 1900 and 1920 origins*



*For both equations, the independent variables are SPR, SLF, PLF, RNG, and CAR. Residuals and first flight dates are plotted in standardized units. See Fig. D.1 for further explanation.

Fig. D.2—Residual scatterplots for equations having 1930 and 1940 origins*



*For both equations, the independent variables are SPR, SLF, PLF, RNG, and CAR. Residuals and first flight dates are plotted in standardized units. See Fig. D.1 for further explanation.

Fig. D.3—Residual scatterplots for equations having 1942 and 1945 origins*

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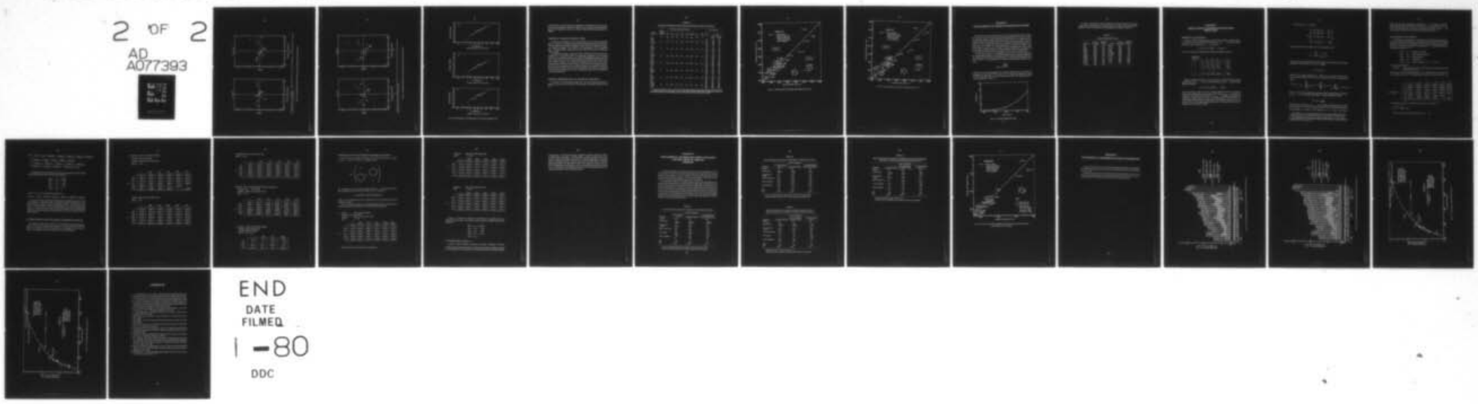

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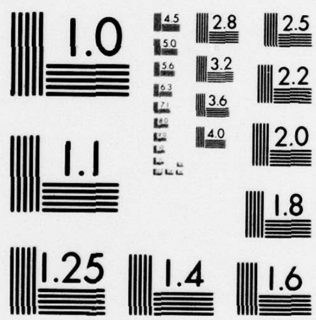

MICROCOPY RESOLUTION TEST CHART
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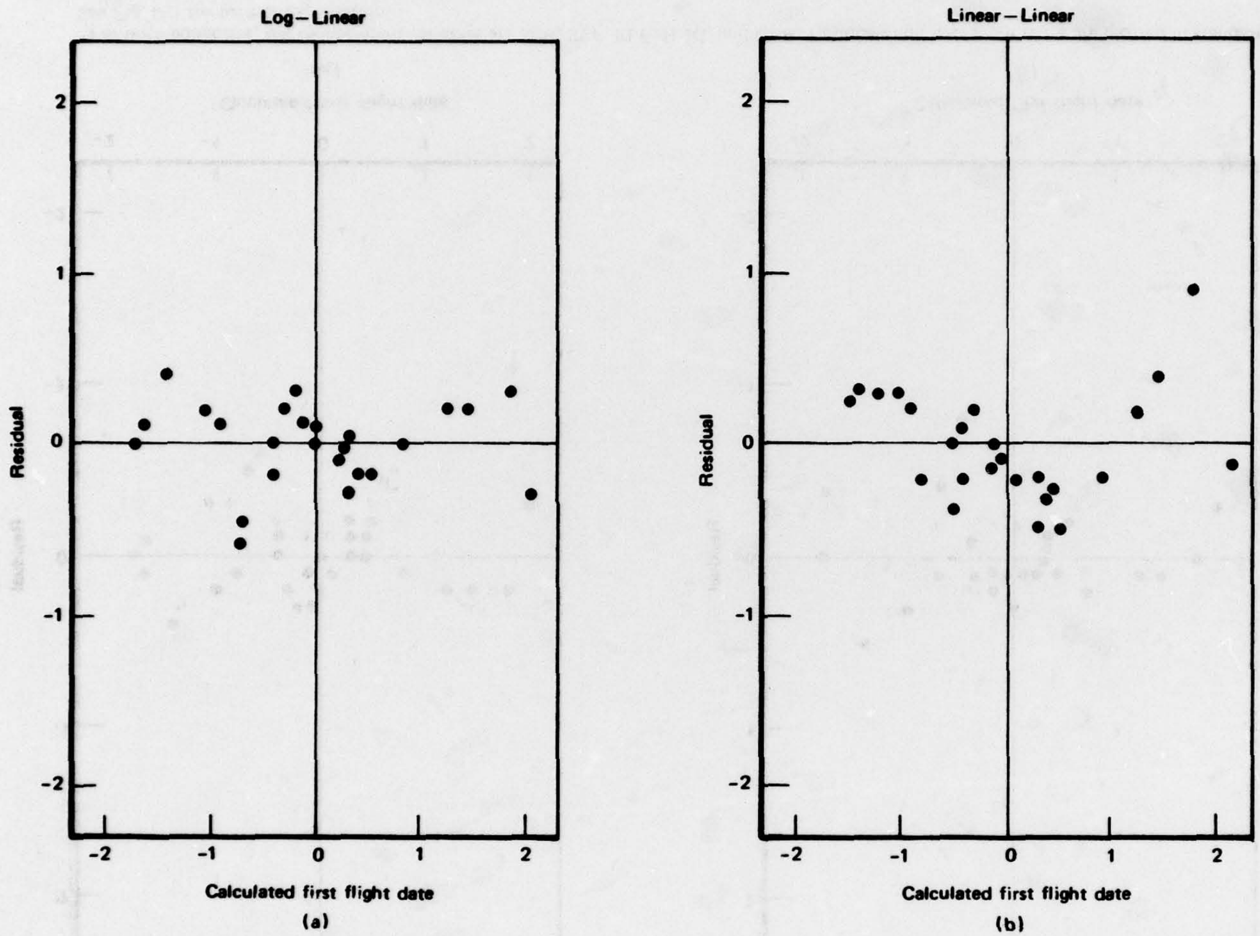
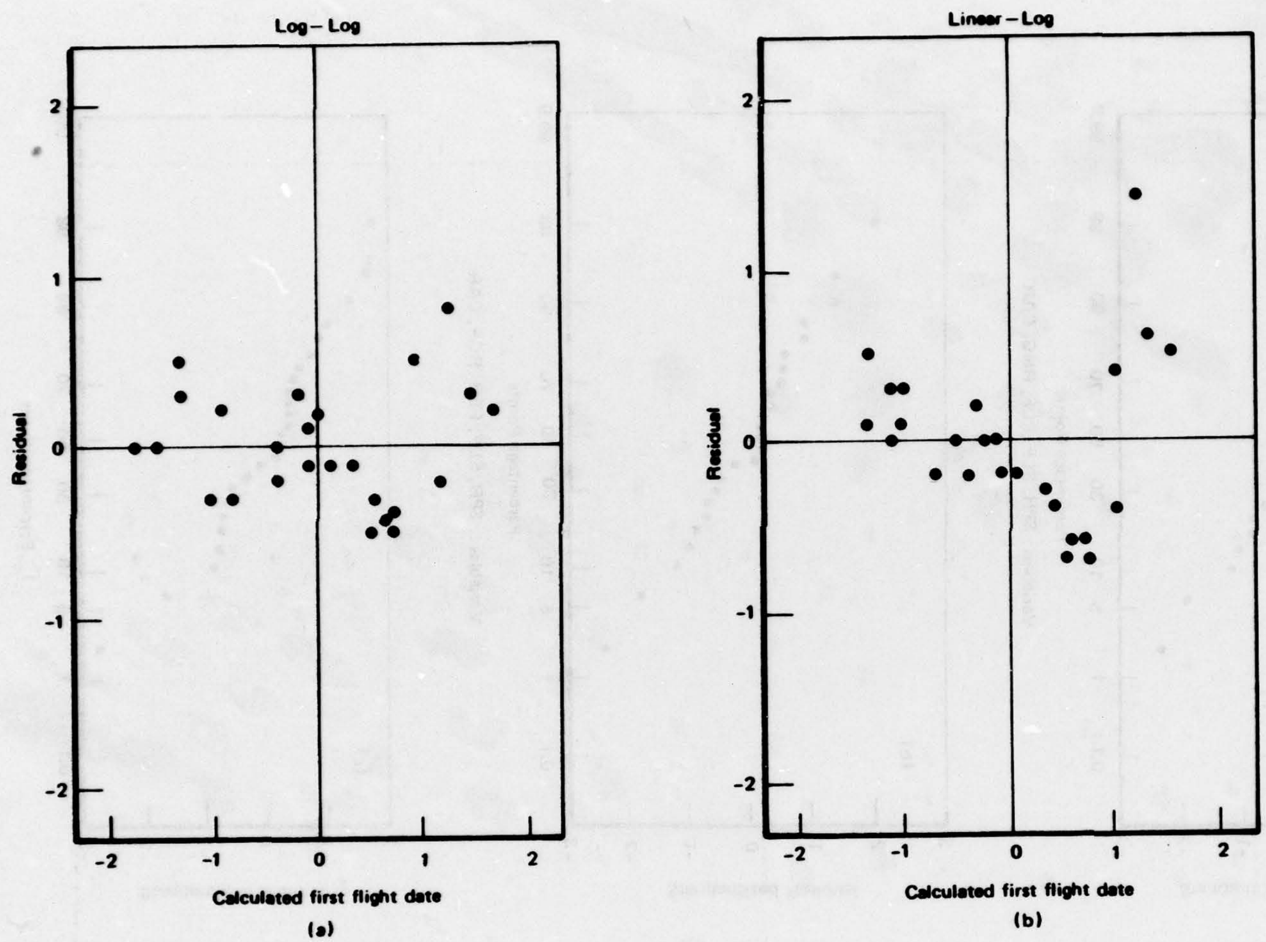


*For both equation forms, the independent variables are SPR, SLF, PLF, RNG, and CAR. Residuals and first flight dates are plotted in standardized units. See Fig. D.1 for further explanation.

Fig. D.4—Residual scatterplots for log-linear and linear-linear equation forms*



*For both equation forms, the independent variables are SPR, SLF, PLF, RNG, and CAR. Residuals and first flight dates are plotted in standardized units. See Fig. D.1 for further explanation.

Fig. D.5—Residual scatterplots for log-log and linear-log equation forms*

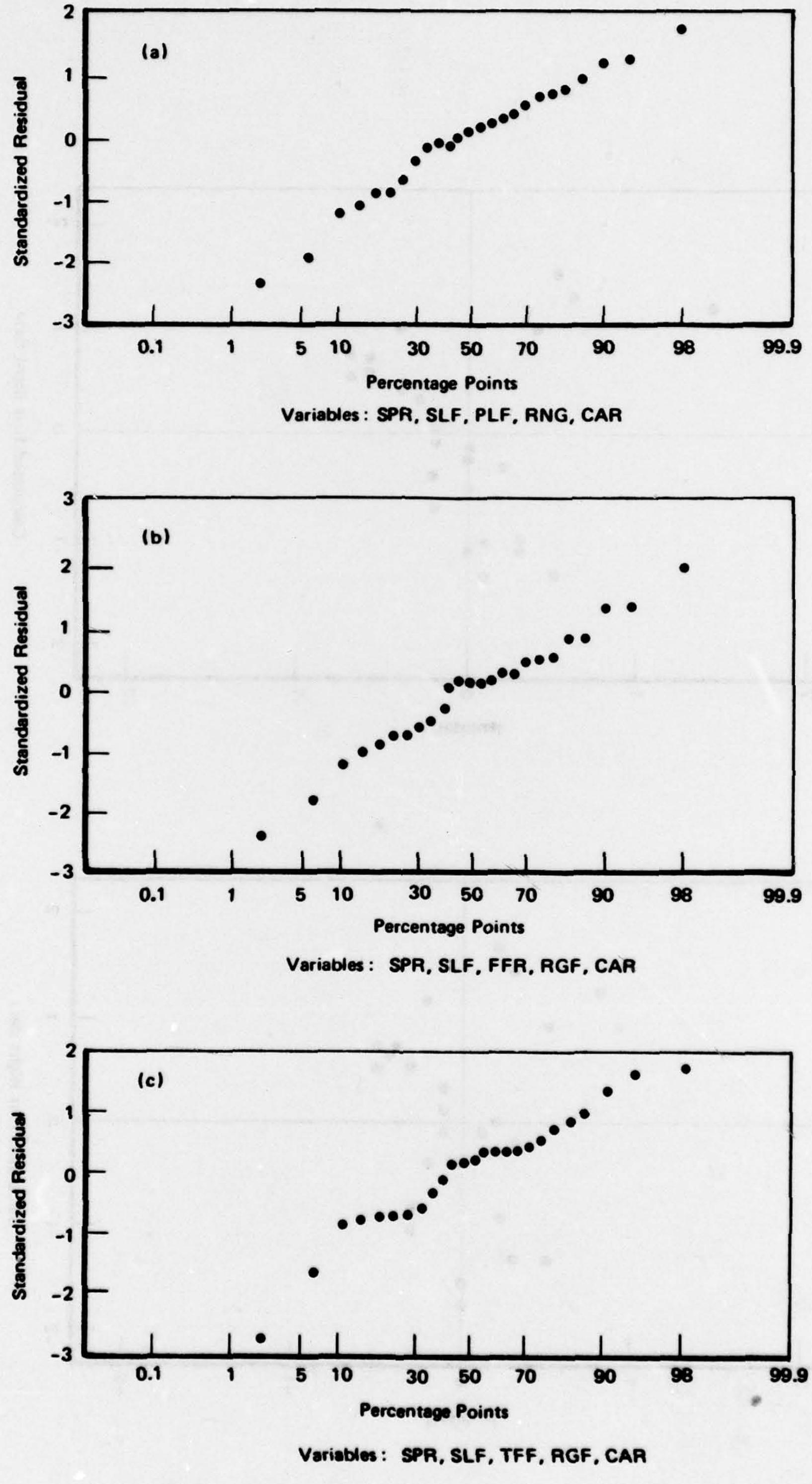


Fig. D.6—Distribution of residuals shown on normal probability grid

residuals follow a normal distribution, although the small sample size makes it difficult to draw definitive conclusions. Without such a tendency toward normality, some of the statistical criteria (e.g., confidence bands) would have diminished reliability.

TECHNOLOGY EQUATION STABILITY CHECK

To test for the stability of one of the primary U.S. technology expressions (Eq. (1) of Sec. III), we randomly excluded five aircraft (20 percent of the sample) and then refitted the technology equation. Table D.5 shows the results from seven such random exclusions. The coefficient of determination (R^2) and standard error of estimate (SEE) remained quite stable, and the signs of the coefficients never changed.

The maximum changes in value for the five coefficients and the constant term ranged from 7 to 67 percent. When we inserted the parameters for the excluded aircraft into the refitted expressions, the predicted first flight dates usually changed only a few months from the estimate based on the full 25 aircraft sample, with some notable exceptions. The calculated first flight dates for some of the more contemporary aircraft (such as the F-111A, F-15A, and F-16A) changed considerably. This result, together with the observed changes in the equation coefficients, reinforces the notion that with such a small sample size, the inclusion or exclusion of a particular aircraft model can have a considerable influence on the definition of the technology trend.

GRAPHICAL REPRESENTATION OF TECHNOLOGY EQUATIONS

We plotted the calculated first flight date versus the actual first flight date using Eqs. (2) and (3) from Table 10. These results are depicted in Figs. D.7 and D.8.

Table D.5

Summary of Random Data Point Exclusions for Sample of New U.S. Designs

Aircraft Excluded	Number of Aircraft in Sample	Coefficients of Independent Variables: SPR	SLF	PLF	RNG	CAR	Constant	R^2	SEE	First Flight Date*: Actual	Calculated: Full Sample	Calculated: Reduced Sample
None	25	.065	1.409	.939	.406	−.093	3.878	.945	.117			
F3D-1										122	114	109
F4D-1										174	169	181
F-101A	20	.071	1.537	.674	.292	−.102	4.002	.950	.123	177	200	193
F-104A										194	211	214
F-111A										328	300	254
FJ-1										89	85	87
XF10F-1										137	147	147
F-101A	20	.074	1.241	.763	.397	−.087	3.923	.925	.121	177	200	203
F-15A										392	439	461
F-16A										444	390	391
F-94A										115	96	89
F-100A										166	153	149
F-101A	20	.064	1.499	.869	.444	−.110	3.820	.953	.114	177	200	197
F-4B										255	250	247
F-14A										372	336	342
F9F-6										147	146	142
F-101A										177	200	202
F-102A	20	.084	1.172	.850	.380	−.101	3.901	.950	.118	187	163	160
F-4B										255	250	269
F-15A										392	439	498
FJ-1										89	85	88
F9F-2										107	131	140
XF10F-1	20	.067	1.282	1.214	.441	−.125	3.838	.947	.112	137	147	150
F-100A										166	153	148
F-15A										392	439	447
FJ-1										89	85	84
F-89A										127	120	118
F9F-6	20	.063	1.401	1.023	.404	−.073	3.850	.934	.130	147	146	143
F3H-2										184	178	174
F-14A										372	336	325
F3D-1										122	114	110
F-102A										187	163	156
F-105B	20	.077	1.368	.314	.243	−.148	4.131	.949	.109	197	198	180
F-111A										328	300	228
F-16A										444	390	352

*Measured in months since January 1, 1940. Numbers under the "Full Sample" column represent the calculated first flight date based on the regression equation for the full sample of 25 new U.S. fighter designs. Numbers under the "Reduced Sample" column represent the calculated first flight date based on the regression equation for 20 aircraft, with the five indicated aircraft excluded.

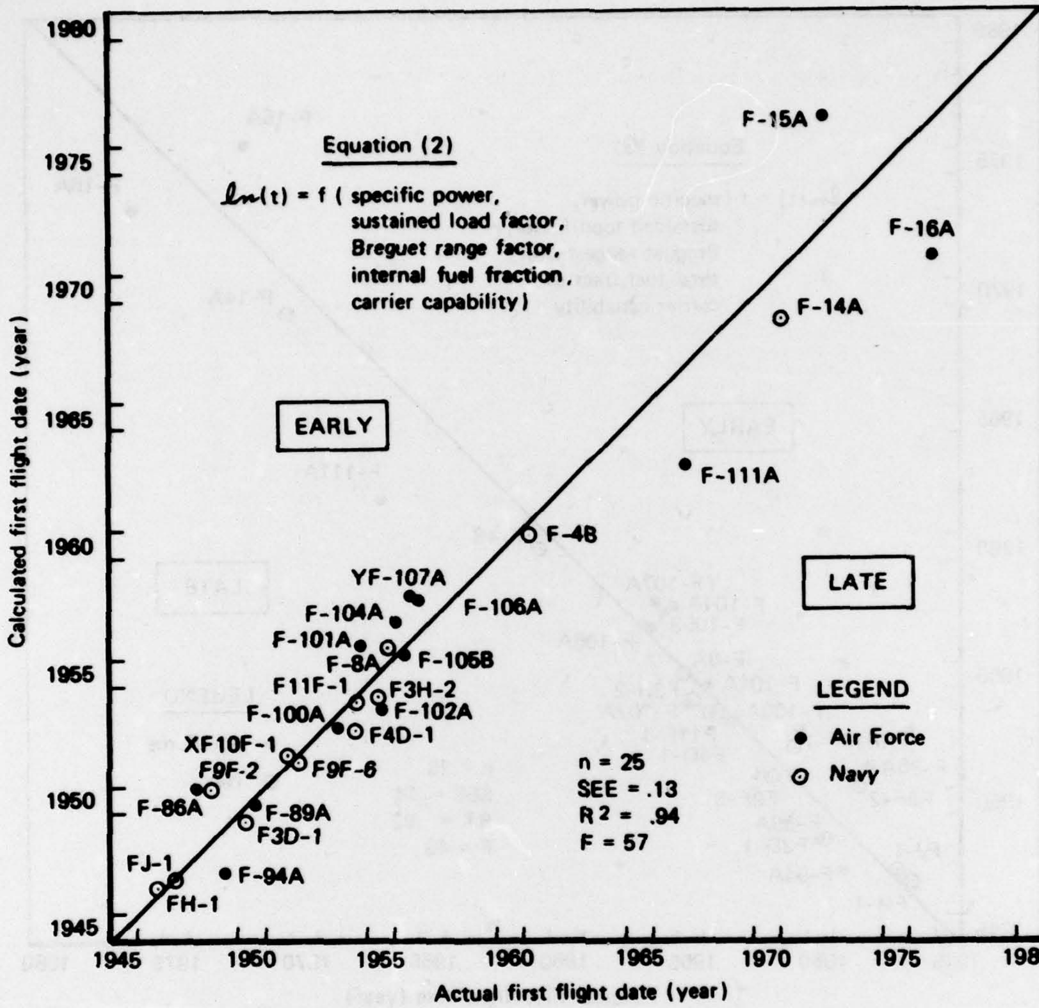


Fig. D.7—Multivariable technology trend defined by Eq. (2)

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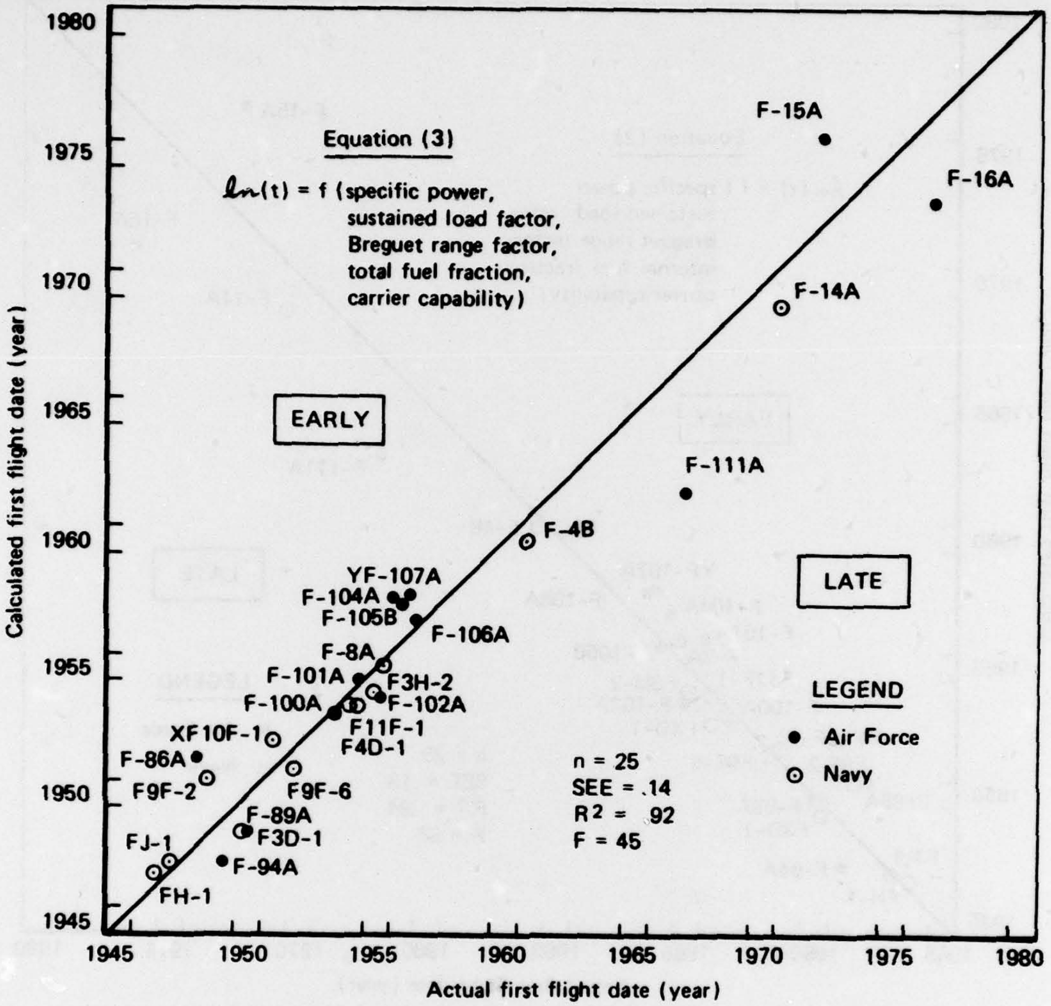

Fig. D.8—Multivariable technology trend defined by Eq. (3)

Appendix E
DEVELOPMENT OF AIRCRAFT WEIGHTING SCHEME

Because 80 percent of the aircraft in our new design sample flew before 1960, and because we are concerned about developing expressions that might be useful for predicting fighter aircraft performance for the future, we considered several weighting schemes that would place more emphasis on the performance trends exhibited by the contemporary aircraft in our sample (the 20 percent having first flight dates after 1960). The uneven distribution of aircraft first flight events through time caused us to reject a simple sequential weighting scheme that would have assigned a weight between 1 and 25 according to the order of appearance of each aircraft (the FH-1 would have a weight of 1, the F-16A a weight of 25).

To take into account in our weighting scheme the time intervals separating the aircraft flight events, we computed the weights using an exponential function. The earliest model (the FH-1) appeared at time t = 82 months and the latest model (the F-16A) at t = 444 months, so we developed an exponential function of the form

$$W(t) = r^{\frac{t-82}{444-82}} ,$$

where W(t) is the weight assigned to an aircraft appearing at time t months. We arbitrarily set the value of the constant r at 11, to place equal emphasis on those aircraft flying after 1960 as on those flying before 1960. The weighting function is shown graphically in Fig. E.1.

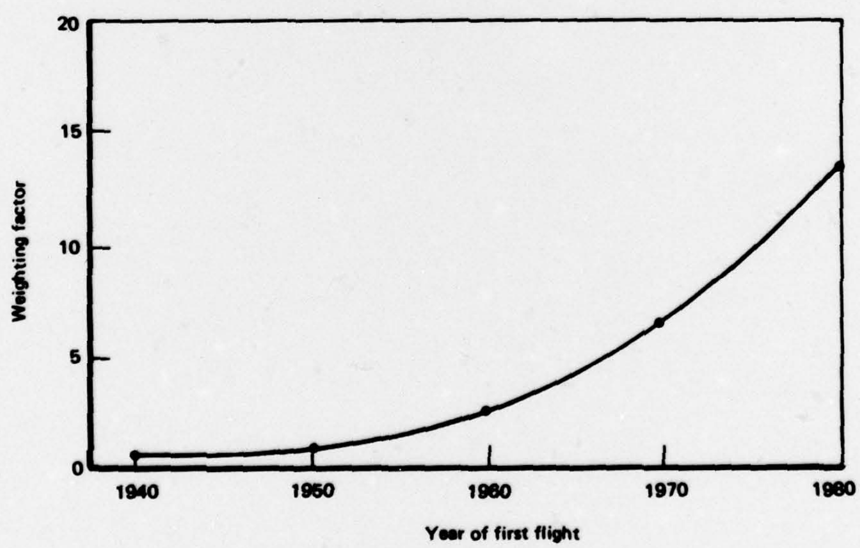

Fig. E.1—Aircraft weighting function

In order to perform the statistical analysis on the basis of 25 aircraft, we had to scale down each weight by a constant factor of 25/67 to get the individual weights to sum to 25. We show the final assignment of weights in Table E.1.

Table E.1

AIRCRAFT WEIGHTING FACTORS

Aircraft	Year of First Flight	Weighting Factor	Aircraft	Year of First Flight	Weighting Factor
FH-1	1946	.373	F3H-2	1955	.733
FJ-1	1947	.391	F-102A	1955	.748
F-86A	1948	.423	F-8A	1955	.758
F9F-2	1948	.440	F-104	1956	.784
F-94A	1949	.464	F-105B	1956	.799
F3D-1	1950	.486	YF-107A	1956	.821
F-89A	1950	.503	F-106A	1956	.837
XF10F-1	1951	.537	F-4B	1961	1.174
F9F-6	1952	.574	F-111A	1967	1.903
F-100A	1953	.651	F-14A	1970	2.548
F4D-1	1954	.686	F-15A	1972	2.908
F11F-1	1954	.691	F-16A	1976	4.104
F-101A	1954	.700			

Appendix F

DERIVATION OF CONFIDENCE BANDS FOR PREDICTION

THEORETICAL BACKGROUND

Suppose a model is postulated in which a dependent variable y is approximated by a linear function of k independent variables $x_1, x_2, \ldots, x_k$. That is, assume that there exist constants $b_0, b_1, \ldots, b_k$ such that

$$y = b_0 + b_1x_1 + b_2x_2 + \ldots + b_kx_k + \epsilon ,$$

where ϵ is an error term. Suppose that n sample observations are given:

Observation Number	y	x_1	x_2	x_3	...	x_k
1	y_1	x_{11}	x_{12}	x_{13}	...	x_{1k}
2	y_2	x_{21}	x_{22}	x_{23}		x_{2k}
3	y_3	x_{31}	x_{32}	x_{33}	...	x_{3k}
...	...	...	...	...	...	...
n	y_n	x_{n1}	x_{n2}	x_{n3}	...	x_{nk}

Based on these observations, we can (by means of regression analysis) obtain estimates $\hat{b}_0, \hat{b}_1, \hat{b}_2, \ldots, \hat{b}_k$ of the coefficients $b_0, b_1, b_2, \ldots, b_k$ so that the regression equation

$$\hat{y} = \hat{b}_0 + \hat{b}_1x_1 + \hat{b}_2x_2 + \ldots + \hat{b}_kx_k$$

serves not only as a "best" fit to the n sample observations but also, one would hope, acts as a good predictor for y given a set of values $x_1, x_2, \ldots, x_k$. More specifically, we would like to use values for $x_1, x_2, \ldots, x_k$ from some observation outside the original sample to obtain a good estimate $\hat{y}$ for the true value y. A clear measure of the usefulness of the model is the confidence with which we can assert that y is within certain specified bounds of $\hat{y}$. We describe below the computation of these confidence bands.

Let X be the $n \times (k+1)$ matrix

$$X = \begin{pmatrix} 1 & x_{11} & x_{12} & x_{13} & \cdots & x_{1k} \\ 1 & x_{21} & x_{22} & x_{23} & \cdots & x_{2k} \\ 1 & x_{31} & x_{32} & x_{33} & \cdots & x_{3k} \\ & & \cdots & & & \\ 1 & x_{n1} & x_{n2} & x_{n3} & \cdots & x_{nk} \end{pmatrix}$$

and suppose that $\hat{\sigma}$ is the *standard error of the estimate*, that is

$$\hat{\sigma}^2 = \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{n-k-1},$$

where y_i and $\hat{y}_i$ are the actual and predicted values corresponding to the ith sample observation.[1] Let S be the $(k+1) \times (k+1)$ matrix

$$S = \hat{\sigma}^2 \ (X^T X)^{-1} ,$$

where X^T is the matrix transpose of X. Finally, let s_{ij} denote the entry in the ith row and jth column of S. Then the *root mean square error* for $y - \hat{y}$ is given by $\tilde{\sigma}$, where

$$\tilde{\sigma}^2 = \hat{\sigma}^2 + s_{11} + \sum_{i=2}^{k+1} s_{ii}\, x_{i-1}^{\ 2} + 2 \sum_{i=2}^{k+1} s_{1i} x_{i-1} + 2 \sum_{2 \leq i < j \leq k+1} s_{ij} x_{i-1} x_{j-1} ,$$

where y and $\hat{y}$ are the actual and predicted values corresponding to the values $x_1, x_2, \ldots, x_k$ of some future observation. Expressed in matrix notation,

$$\tilde{\sigma}^2 = \hat{\sigma}^2 + \vec{x} S \vec{x}^T ,$$

where $\vec{x}$ is the vector $(1, x_1, x_2, \ldots, x_k)$. In terms of confidence bands, we can say that based on our belief in the trends established by the n sample observations, the probability is $1 - a$ that y will lie within $t(n-k-1, 1-\frac{\alpha}{2})\,\tilde{\sigma}$ of $\hat{y}$.[2] Here t

[1] The difference $y_i - \hat{y}_i$ is commonly referred to as the ith *residual*. Moreover, under our modeling assumptions, $\hat{\sigma}^2$ is an unbiased estimate of the true variance σ^2 of the error term.

[2] Assuming that the error terms ϵ_i are normally distributed with mean 0 and variance σ^2. Notation follows that of N. R. Draper and H. Smith, *Applied Regression Analysis*, John Wiley & Sons, Inc., New York, 1966, p. 19.

denotes the Student t-distribution evaluated for n - k - 1 degrees of freedom. This confidence band lies between two branches of a quadric surface that surrounds the regression plane. The band is narrowest at the point $(\bar{x}_1, \bar{x}_2, \ldots, \bar{x}_k)$ and increases in width as one moves away from this central point.[3]

ILLUSTRATION OF THE THEORY

To illustrate these techniques, we will carry out the confidence band computation for an equation describing the technology trend for the 25 new U.S. fighter designs. We will use Eq. (1) introduced in Sec. III, which uses the log-linear equation form. In this case, the number of observations is n = 25 and the number of independent variables is k = 5:

SPR = x_1 = Specific power/100

SLF = x_2 = Sustained load factor/10

PLF = x_3 = Payload fraction

RNG = x_4 = Range/1000

CAR = x_5 = Carrier capability ("no" = 1, "yes" = 0)

The dependent variable is:

ln (FFT) = Natural logarithm of the first flight date (measured in months since January 1, 1940)

The matrix X thus has dimensions 25 × 6. The standard error of estimate $\hat{\sigma}$ for this regression was .117. A straightforward computer calculation shows that

$S = \hat{\sigma}^2 (X^T X)^{-1} =$

	1	x_1	x_2	x_3	x_4	x_5
1	.01531	.00084	-.01864	-.03357	-.00667	-.00021
x_1	.00084	.00018	-.00303	-.00257	-.00039	-.00009
x_2	-.01864	-.00303	.10602	.02912	.00285	-.00267
x_3	-.03357	-.00257	.02912	.12801	.01340	-.00045
x_4	-.00667	-.00039	.00285	.01340	.00449	0
x_5	-.00021	-.00009	-.00267	-.00045	0	.00265

As described above, the root mean square error for $y - \hat{y}$ is given by

$\tilde{\sigma} = \sqrt{\hat{\sigma}^2 + \vec{x} S \vec{x}^T}$. Thus

[3]Here $\bar{x}_i$ is the mean of the observed values $x_{1i}, x_{2i}, \ldots, x_{ni}$.

$$\tilde{\sigma}^2 = .11716^2 + .01531 + .00018x_1^{\ 2} + .10602x_2^{\ 2} + .12801x_3^{\ 2} + .00449x_4^{\ 2} + .00265x_5^{\ 2}$$

$$+ 2(.00084x_1 - .01864x_2 - .03357x_3 - .00667x_4 - .00021x_5)$$

$$+ 2(-.00303x_1x_2 - .00257x_1x_3 - .00039x_1x_4 - .00009x_1x_5 + .02912x_2x_3$$

$$+ .00285x_2x_4 - .00267x_2x_5 + .01340x_3x_4 - .00045x_3x_5 + 0x_4x_5) \cdot$$

To illustrate the use of this error term, suppose it is proposed to build a (hypothetical) fighter described by the following parameters:

$$\begin{aligned} \text{SPR} &= x_1 = 16.089 \\ \text{SLF} &= x_2 = .502 \\ \text{PLF} &= x_3 = .292 \\ \text{RNG} &= x_4 = 1.475 \\ \text{CAR} &= x_5 = 1 \end{aligned}$$

As given in Sec. III, the regression equation (1) is:

$$\ln(\text{FFT}) = 3.878 + .065\ \text{SPR} + 1.409\ \text{SLF} + .939\ \text{PLF} + .406\ \text{RNG} - .093\ \text{CAR}.$$

The equation yields a calculated first flight date in logarithmic terms of 6.411, or late 1990. If we evaluate $\tilde{\sigma}$ at the above parameter values, we find that $\tilde{\sigma} = .1454$. The 90 percent confidence interval is defined by 6.411 - [1.729] [.1454] and 6.411 + [1.729] [.1454], or 1979 and 2005. Based on past trends in fighter technology, we would thus expect with 90 percent confidence that the United States could fly an aircraft possessing the characteristics noted above sometime between 1979 and 2005.

CONFIDENCE BAND DATA FOR SELECTED REGRESSION EQUATIONS

We present the matrices $S = \hat{\sigma}^2(X^TX)^{-1}$ that permit the construction of confidence bands for five representative variable set, sample space combinations, three for the sample of 25 new U.S. designs, one for a sample of 39 new and derivative U.S. designs, and one for a sample of 13 new Soviet designs.

A. Sample: 25 New U.S. Fighter Designs

Equation Form: Log-Linear

Variables: SPR, SLF, PLF, RNG, CAR

SEE: $\hat{\sigma}$ = .117

S =

	1	SPR	SLF	PLF	RNG	CAR
1	.01531	.00084	-.01864	-.03357	-.00667	-.00021
SPR	.00084	.00018	-.00303	-.00257	-.00039	-.00009
SLF	-.01864	-.00303	.10602	.02912	.00285	-.00267
PLF	-.03357	-.00257	.02912	.12801	.01340	-.00045
RNG	-.00667	-.00039	.00285	.01340	.00449	0
CAR	-.00021	-.00009	-.00267	-.00045	0	.00265

Variables: SPR, SLF, FFR, RGF, CAR

SEE: $\hat{\sigma}$ = .125

S =

	1	SPR	SLF	FFR	RGF	CAR
1	.02749	.00069	-.00702	-.01102	-.05270	.00113
SPR	.00069	.00016	-.00277	-.00068	-.00103	-.00010
SLF	-.00702	-.00277	.12156	.01837	-.03392	-.00102
FFR	-.01102	-.00068	.01837	.07090	-.04155	.00420
RGF	-.05270	-00103	-.03392	-.04155	.18324	-.00810
CAR	.00113	-.00010	-.00102	.00420	-.00810	.00347

Variables: SPR, SLF, TFF, RGF, CAR
SEE: $\hat{\sigma}$ = .140

	1	SPR	SLF	TFF	RGF	CAR
1	.04471	.00177	-.01672	-.02655	-.07357	.00278
SPR	.00177	.00028	-.00419	-.00221	-.00178	-.00002
SLF	-.01672	-.00419	.15608	.02432	-.02897	-.00314
S = TFF	-.02655	-.00221	.02432	.05599	-.00027	-.00117
RGF	-.07358	-.00178	-.02896	-.00027	.19794	-.00702
CAR	.00278	-.00002	-.00314	-.00117	-.00702	.00404

B. Sample: 39 U. S. Fighter Designs (New and Derivative)
Equation Form: Log-Linear
Variables: SPR, SLF, PLF, RNG, CAR
SEE: $\hat{\sigma}$ = .157

	1	SPR	SLF	PLF	RNG	CAR
1	.01981	.00071	-.01759	-.03691	-.00908	-.00051
SPR	.00071	.00016	-.00222	-.00187	-.00040	-.00005
SLF	-.01759	-.00222	.11298	.00354	.00104	-.00574
S = PLF	-.03691	-.00187	.00354	.12861	.01772	-.00060
RNG	-.00908	-.00040	.00104	.01772	.00598	.00041
CAR	-.00051	-.00005	-.00574	-.00060	.00041	.00322

C. Sample: 13 New Soviet Fighter Designs
Equation Form: Linear-Linear
Variables: SPR, PLF, RNG
SEE: $\hat{\sigma}$ = 18.1 months

	1	SPR	PLF	RNG
1	334.9	-9.1	-594.5	-1475.3
SPR	-9.1	3.8	-101.1	-38.8
PLF	-594.5	-101.1	10126.5	-317.2
RNG	-1475.3	-38.8	-317.2	15854.0

CONFIDENCE BANDS FOR WEIGHTED REGRESSION EQUATIONS

Suppose that the n sample observations are assigned the respective weights $w_1, w_2, \ldots, w_n$.* Let W be the n x n diagonal matrix

$$W = \begin{pmatrix} w_1 & & \text{\Large 0} \\ & w_2 & \\ \text{\Large 0} & & \ddots \\ & & & w_n \end{pmatrix}$$

The computation of the root mean square error for $y - \hat{y}$ is identical to that for the unweighted case except that the matrix S is now computed as

$$S = \hat{\sigma}^2 \left(X^T W X\right)^{-1} \left(X^T W^2 X\right) \left(X^T W X\right)^{-1},$$

where $\hat{\sigma}$ is the standard error of the estimate for the corresponding *unweighted* regression equation.

We now present this matrix S, incorporating weighting, for the same three variable sets and equation forms used in (A) of the previous subsection.

A. Sample: 25 New Fighter Designs
Equation Form: Log-Linear
Variables: SPR, SLF, PLF, RNG, CAR
SEE: $\hat{\sigma} = .117$

S =

	1	SPR	SLF	PLF	RNG	CAR
1	.02582	.00179	-.04727	-.05959	-.00951	-.00034
SPR	.00179	.00030	-.00604	-.00524	-.00066	-.00010
SLF	-.04727	-.00604	.20065	.10081	.00915	-.00304
PLF	-.05959	-.00524	.10081	.19918	.02043	.00038
RNG	-.00951	-.00066	.00915	.02043	.00580	-.00038
CAR	-.00034	-.00010	-.00304	.00038	-.00038	.00380

*Appendix E describes the rationale used to assign weights.

Variables: SPR, SLF, FFR, RGF, CAR

SEE: $\hat{\sigma}$ = .125

		1	SPR	SLF	FFR	RGF	CAR
	1	.03777	.00136	-.03259	-.01942	-.06196	.00140
	SPR	.00136	.00025	-.00565	-.00163	-.00108	-.00015
S =	SLF	-.03259	-.00565	.25141	.05547	-.05060	.00235
	FFR	-.01942	-.00163	.05547	.09977	-.06007	.00774
	RGF	-.06196	-.00108	-.05060	-.06007	.23397	-.01393
	CAR	.00140	-.00015	.00235	.00774	-.01393	.00457

Variables: SPR, SLF, TFF, RGF, CAR

SEE: $\hat{\sigma}$ = .140

		1	SPR	SLF	TFF	RGF	CAR
	1	.06740	.00337	-.06168	-.04506	-.09580	.00573
	SPR	.00337	.00044	-.00840	-.00388	-.00288	.00016
	SLF	-.06168	-.00839	.30419	.06802	-.01563	-.00808
S =	TFF	-.04507	-.00388	.06803	.07948	.00681	-.00252
	RGF	-.09580	-.00288	-.01563	.00680	.24750	-.01228
	CAR	.00573	.00016	-.00808	-.00252	-.01228	.00517

Finally, to compare the predictive characteristics of a weighted versus unweighted equation form, we consider the same hypothetical fighter design having parameters

$$\begin{aligned} \text{SPR} &= x_1 = 16.089 \\ \text{SLF} &= x_2 = .502 \\ \text{PLF} &= x_3 = .292 \\ \text{RNG} &= x_4 = 1.475 \\ \text{CAR} &= x_5 = 1 \end{aligned}$$

The weighted regression equation is:

$$\ln(\text{FFT}) = 3.675 + .045\,\text{SPR} + 1.903\,\text{SLF} + 1.452\,\text{PLF} + .495\,\text{RNG} - .120\,\text{CAR}.$$

It follows that the calculated value of ln(FFT) for this fighter is 6.388, equivalent to a first flight date of mid-1989. If we evaluate $\tilde{\sigma}$ at the above parameter values,

we find that $\tilde{\sigma}$ = .1523. The 90 percent confidence interval is defined by 6.388 – [1.729] [.1523] and 6.388 + [1.729] [.1523], or 1978 and 2004. Thus if past trends in fighter technology (along with our weighting assumptions) accurately reflect future design trends, we would expect that the United States could fly an aircraft possessing the characteristics noted above sometime between 1978 and 2004. Comparing the weighted result with the unweighted result presented earlier, we can conclude that our weighting scheme does not demonstrably influence the predictive properties of the technology equation.

Appendix G

SUPPLEMENTAL INFORMATION ABOUT INCLUSION AND EXCLUSION OF CERTAIN AIRCRAFT

To consider the effect of including derivative aircraft, we added first a set of five, and then all 14 derivative aircraft to the sample and reestimated the equation coefficients (see Tables G.1 and G.2). Addition of the set of five derivative aircraft did not change the basic character of the equations; addition of the full set of 14 derivative aircraft caused larger changes in the coefficients.

In evaluating the effect of excluding fighter aircraft that emphasized air-to-ground mission performance, we reestimated the coefficients of technology Eqs. (2) and (3). The results shown in Tables G.3 and G.4 indicate that the exclusion of the F-111A causes a greater change in the equation coefficients than the exclusion of the F-111A, YF-107A, and the F-105B as a group. Equation (3) seems most sensitive to the exclusion of these three aircraft, although Fig. G.1 shows that the fundamental character of the results still do not change. In each case, equations estimated without these air-to-ground fighters in the sample place more emphasis on combat capability and less on cruise capability.

Table G.1

INCLUDING DERIVATIVE AIRCRAFT: COMPARISON WITH EQ. (2) COEFFICIENTS

	Value of Coefficient		
Parameter	25 Aircraft Sample Eq. (2)	30 Aircraft Sample[a]	39 Aircraft Sample (all new and derivative)
Constant	3.64	3.78	3.98
Specific power	.072 (.0001)[b]	.079 (.000001)	.082 (.000001)
Sustained load factor	1.18 (.005)	1.08 (.005)	1.18 (.01)
Breguet range factor	1.26 (.01)	1.21 (.005)	.542 (.2)
Fuel fraction	.876 (.005)	.566 (.02)	.729 (.02)
Carrier capability	−.105 (.1)	−.121 (.05)	−.045 (.5)
R^2	.94	.92	.83
SEE	.125	.133	.179
F	57.2	52.9	31.1

[a]25 "new" designs plus the YF-93A, F-86D, F-84F, F-94C, and the F-86H.

[b]Upper bound for probability of incorrectly rejecting the null hypothesis.

Table G.2

Including Derivative Aircraft: Comparison with Eq. (3) Coefficients

Parameter	25 Aircraft Sample Eq. (3)	30 Aircraft Sample[a]	39 Aircraft Sample (all new and derivative)
	Value of Coefficient		
Constant	3.53	3.66	3.90
Specific power	.059 (.005)[b]	.068 (.0001)	.070 (.001)
Sustained load factor	1.19 (.01)	1.10 (.005)	1.14 (.01)
Breguet range factor	1.77 (.001)	1.44 (.001)	.662 (.1)
Total fuel fraction	.526 (.05)	.516 (.05)	.700 (.02)
Carrier capability	−.168 (.02)	−.169 (.01)	−.091 (.2)
R^2	.92	.92	.83
SEE	.140	.134	.179
F	45.2	51.8	31.5

[a]25 "new" designs plus the YF-93A, F-86D, F-84F, F-94C, and the F-86H.

[b]Upper bound for probability of incorrectly rejecting the null hypothesis.

Table G.3

Results from Excluding Aircraft that Emphasize Air-to-Ground Mission Performance: Comparison with Equation (2) Coefficients

Parameter	22 Aircraft Sample[a]	24 Aircraft Sample (excludes F-111A)	25 Aircraft Sample Eq. (2)
	Value of Coefficient		
Constant	3.85	3.87	3.64
Specific power	.073 (.0001)[b]	.073 (.00001)	.072 (.0001)
Sustained load factor	1.41 (.002)	1.42 (.001)	1.18 (.005)
Breguet range factor	.938 (.1)	.913 (.1)	1.26 (.01)
Fuel fraction	.581 (.1)	.554 (.1)	.876 (.005)
Carrier capability	−.136 (.05)	−.138 (.05)	−.105 (.1)
R^2	.94	.94	.94
SEE	.123	.117	.125
F	53.9	60.8	57.2

[a]Excludes F-105B, YF-107A, and the F-111A.

[b]Upper bound for probability of incorrectly rejecting the null hypothesis.

Table G.4

RESULTS FROM EXCLUDING AIRCRAFT THAT EMPHASIZE AIR-TO-GROUND MISSION PERFORMANCE: COMPARISON WITH EQUATION (3) COEFFICIENTS

	Value of Coefficient		
Parameter	22 Aircraft Sample[a]	24 Aircraft Sample (excludes F-111A)	25 Aircraft Sample Eq. (3)
Constant	3.87	3.89	3.53
Specific power	.069 (.001)[b]	.070 (.001)	.059 (.005)
Sustained load factor	1.45 (.005)	1.46 (.001)	1.19 (.01)
Breguet range factor	1.13 (.1)	1.09 (.05)	1.77 (.001)
Total fuel fraction	.242 (.5)	.223 (.5)	.526 (.05)
Carrier capability	−.175 (.02)	−.179 (.01)	−.168 (.02)
R^2	.94	.94	.92
SEE	.132	.125	.140
F	46.6	52.8	45.2

[a]Excludes F-105B, YF-107A, and the F-111A.

[b]Upper bound for probability of incorrectly rejecting the null hypothesis.

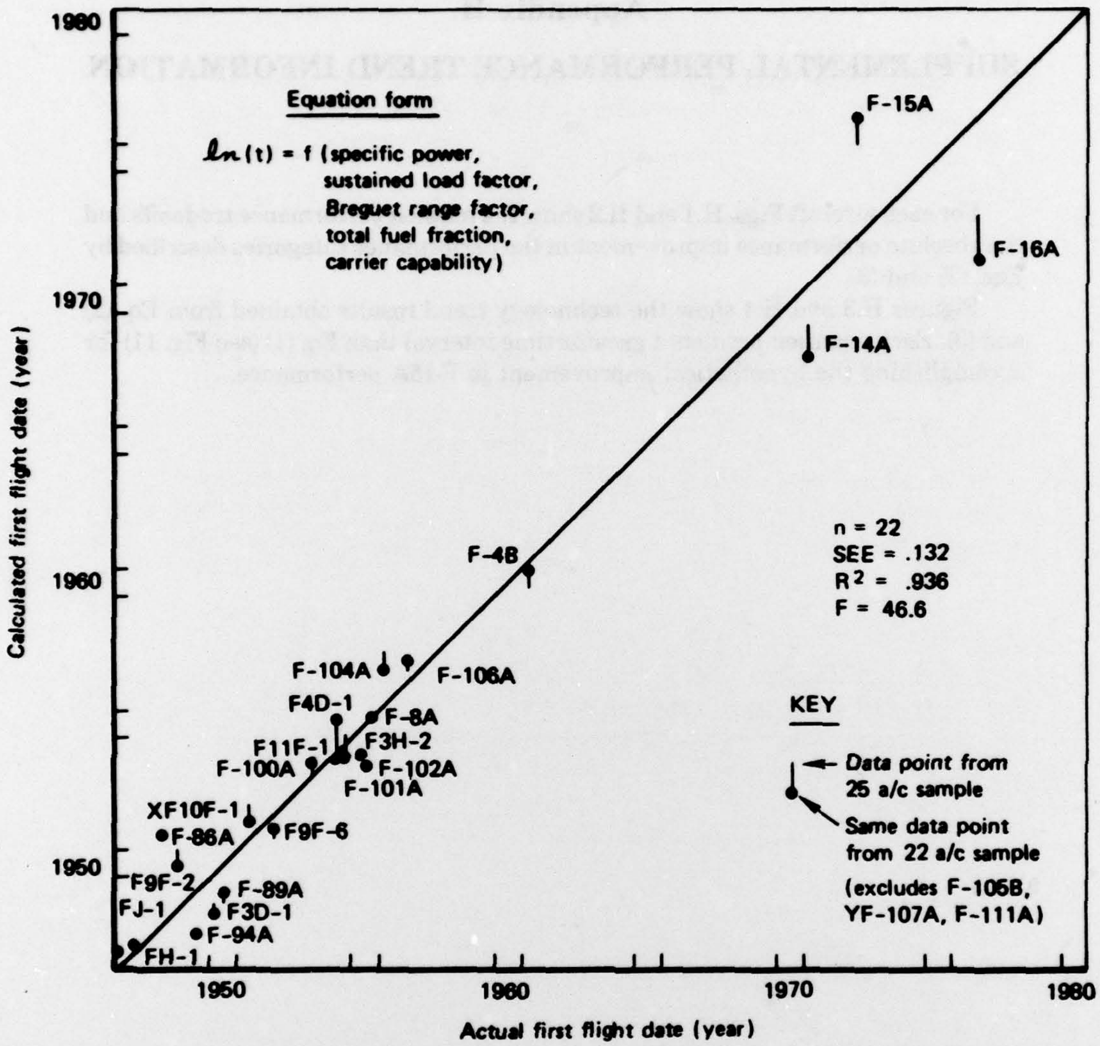

Fig. G.1—Effect of excluding fighters having air-to-ground mission emphasis: results using Eq. (3) variables

Appendix H

SUPPLEMENTAL PERFORMANCE TREND INFORMATION

For each aircraft Figs. H.1 and H.2 show the mission performance tradeoffs and the absolute performance improvement in the performance categories described by Eqs. (2) and (3).

Figures H.3 and H.4 show the technology trend results obtained from Eq. (2) and (3). Each equation predicts a greater time interval than Eq. (1) (see Fig. 11) for accomplishing the hypothetical improvement in F-15A performance.

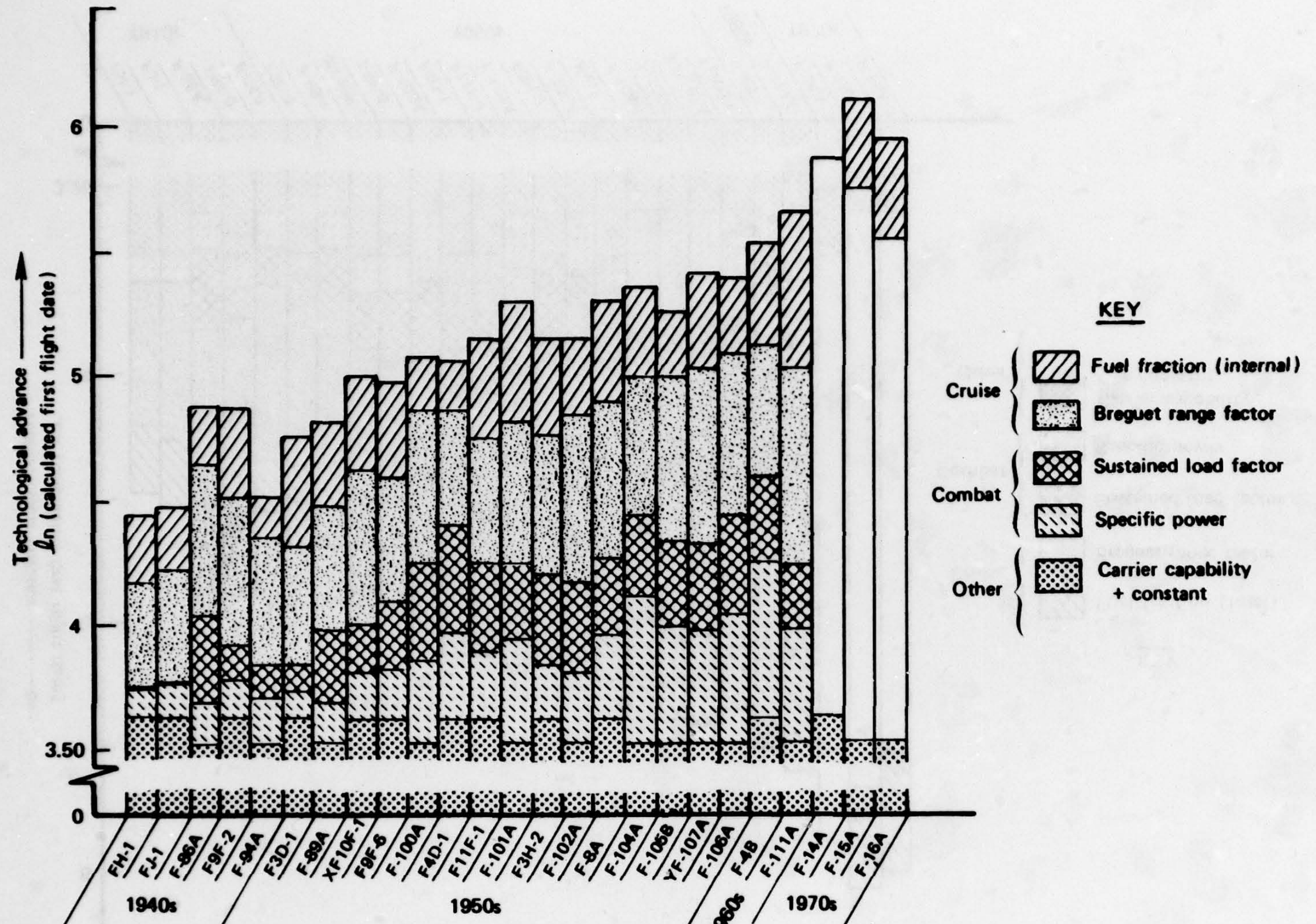

Fig. H.1—Technological advance and mission tradeoffs measured by Eq. (2)

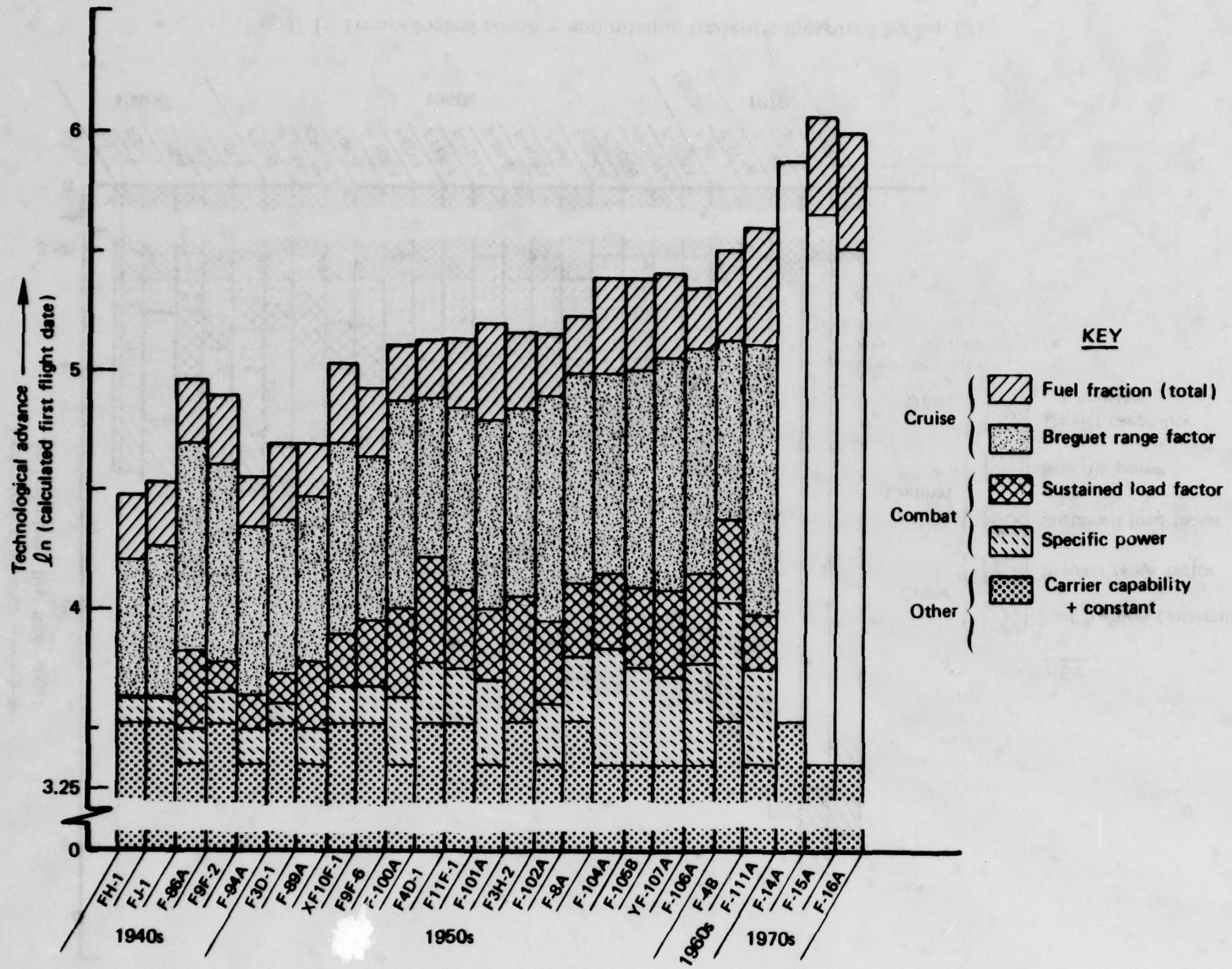

Fig. H.2—Technological advance and mission tradeoffs measured by Eq. (3)

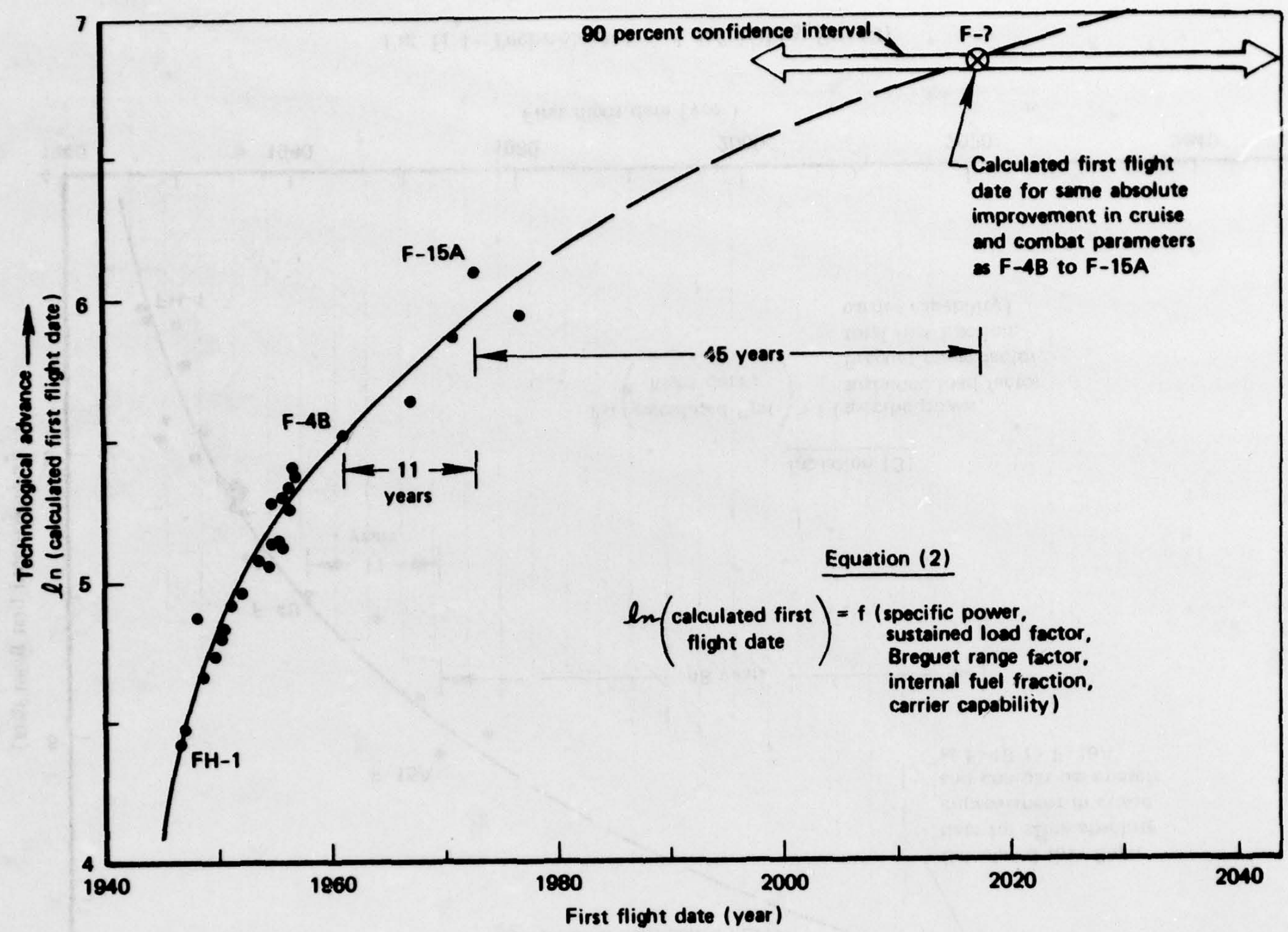

Fig. H.3—Technology trend defined by Eq. (2)

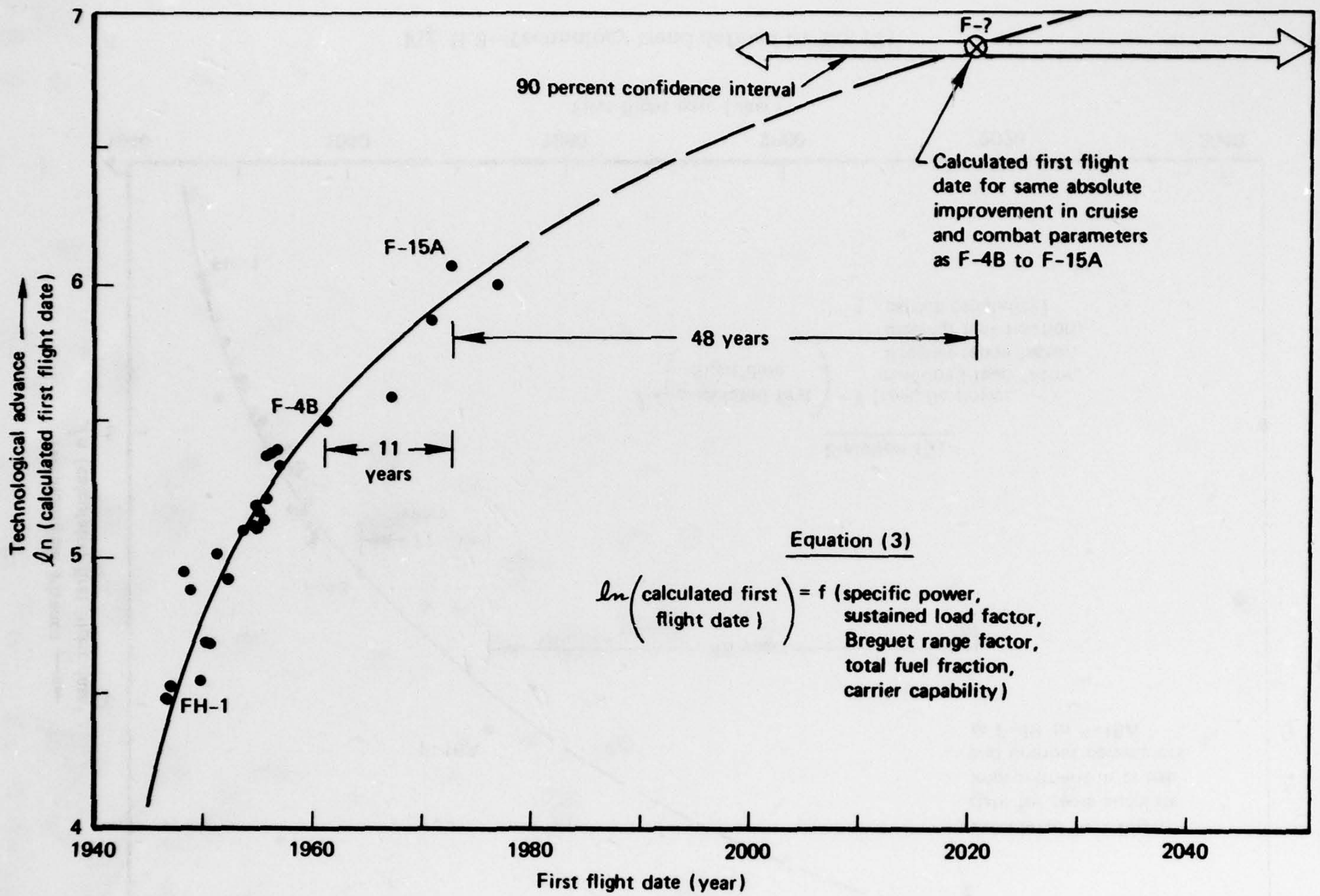

Fig. H.4—Technology trend defined by Eq. (3)

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